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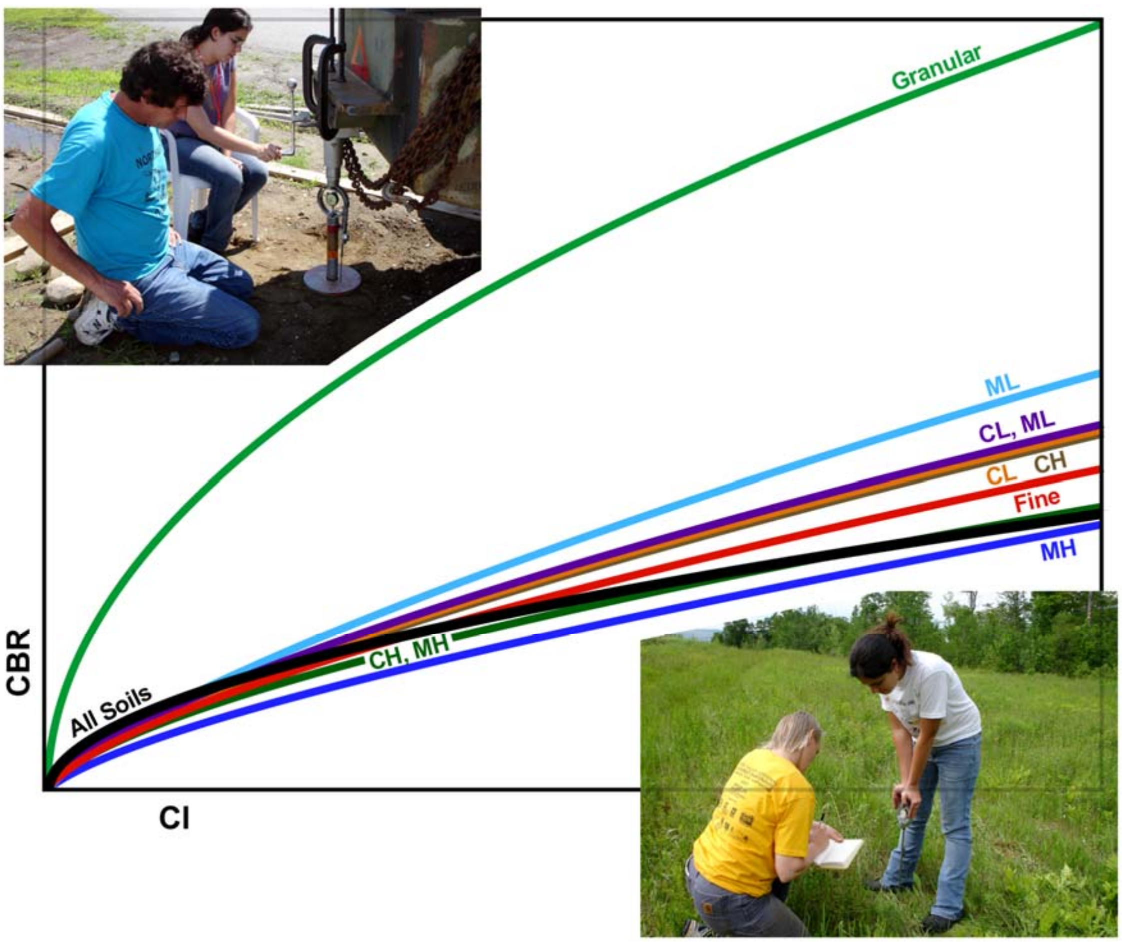
*Opportune Landing Site Program*

# Predicting California Bearing Ratio from Trafficability Cone Index Values

Sally A. Shoop, Deborah Diemand, Wendy L. Wieder, George Mason, and Peter M. Seman

October 2008



*COVER*: Graphic illustrating the correlation between California bearing ratio (CBR) and cone index (CI) strength measures, showing the field test method for each.

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**Abstract:** California bearing ratio (CBR) soil strength measurements are commonly used by the U.S. Air Force to identify locations suitable for use as expedient runways. Field CBR testing is a time-consuming operation requiring a skilled operator, and can be hazardous for the evaluation teams in hostile environments. Limited amounts of published CBR data are available. The measurement of trafficability cone index (CI), widely used by the U.S. Army for similar applications, is a process that is fast and simple, and for which a vast amount of published data worldwide are available. This report describes methods reported in the literature to correlate CBR to CI based on Unified Soil Classification System (USCS) soil type, as well as a systematic program to develop an algorithm to predict CBR from CI using a database of measurements of both CBR and CI made concurrently by the U.S. Army, many of which were taken in undisturbed soil. The database is described and related soil properties, such as plasticity information, soil density, specific gravity, and moisture content, are given.

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# Nomenclature

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| AI | Airfield index |
| AFB | Air Force Base |
| ASAE | American Society of Agricultural Engineers |
| ASTM | American Society for Testing and Materials |
| CBR | California bearing ratio |
| CI | Cone index |
| CRREL | Cold Regions Research and Engineering Laboratory |
| DoD | Department of Defense |
| DCP | Dynamic cone penetrometer |
| DTED | Digital terrain elevation data |
| ERDC | Engineer Research and Development Center |
| FASST | Fast All-Seasons Soil State |
| FM | Field manual |
| ft | Foot |
| GSL | Geotechnical and Structures Laboratory |
| in. | Inch |
| JRAC | Joint Rapid Airfield Construction |
| lb | Pound |
| LL | Liquid limit |

| | |
|---|---|
| NCHRP | National Cooperative Highway Research Program |
| OLS | Opportune Landing Site |
| PI | Plasticity index |
| PL | Plasticity limit |
| pcf | Pounds per cubic foot |
| psi | Pounds per square inch |
| SAE | Society of Automotive Engineers |
| TM | Technical manual |
| TO | Theater of operations |
| U.S. | United States |
| USACE | United States Army Corps of Engineers |
| USAF | United States Air Force |
| USCS | Unified Soil Classification System |

# Preface

This report was prepared by Dr. Sally A. Shoop, Deborah Diemand, and Peter M. Seman, Force Projection and Sustainment Branch, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center (ERDC), Hanover, NH; Dr. Wendy L. Wieder, Consultant, Science and Technology Corporation, Hampton, VA.; and George Mason, Geotechnical and Structures Laboratory, ERDC; the report was reviewed by Rosa Affleck and Lynette Barna, Force Projection and Sustainment Branch, CRREL.

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This report was prepared under the general supervision of Dr. Brad Guay, Chief, Force Projection and Sustainment Branch, CRREL; Dr. Justin B. Berman, Chief, Research and Engineering Division, CRREL; Dr. Lance D. Hansen, Deputy Director, CRREL; and Dr. Robert E. Davis, Director, CRREL.

At the time this work was performed, COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

# 1 Introduction

Current U.S. Army and U.S. Air Force (USAF) procedures for the planning and design of airfields in Theater of Operations (TO) entail several steps (U.S. Army and Air Force 1994b). For an unimproved or expedient-surfaced airfield you must, (1) locate proposed sites of the proper size and geometry, (2) select the design aircraft with its associated gross weight, and (3) measure in-place soil strength. For most military pavement applications, the soils' California bearing ratio (CBR) is used as an empirical measurement of shear strength, one of the two failure mechanisms of soil under load (i.e., bearing capacity) along with settlement (U.S. Army and Air Force 1994b). CBR, obtained from either laboratory or field CBR testing, or by correlation from another soil strength measurement, is used with empirical design and evaluation curves to determine whether the soils at the site can support aircraft operational loads.

To date, soil strength or bearing capacity values for potential landing sites have been provided by advanced military personnel on the ground performing standard field soil bearing tests before the beginning of aircraft operations. In non-hostile environments, specially trained civil engineer personnel conduct these evaluations. In hostile situations, combat control teams conduct the evaluations under clandestine conditions. There are several limitations to the current methods, including compromising the location itself and danger to personnel performing the evaluations in hostile environments.

Compounding the difficulty of physically taking soil strength measurements in the field is the time-consuming test method. Standard CBR laboratory testing requires sampling, transport of soils to a laboratory, and then a four-day testing period. Field CBR tests are also time-intensive and are usually impractical for use in theater (U.S. Army and Air Force 1994b). Therefore, it is USAF standard practice to determine strength using a dynamic cone penetrometer (DCP), and then correlate the DCP readings to a CBR value for use in the empirical design and evaluation method.

Alternatively, when the U.S. Army evaluates or predicts ground strength for vehicle operations, a trafficability cone index (CI) is used. Measurements and predictions of trafficability CI are common for Army terrain analysis and for modeling and simulations of ground-based operations; therefore, relating CI to CBR is useful for tapping into this additional resource. This report presents correlations between CI and CBR based on Unified Soil Classification System (USCS) soil classification or gross soil descriptions and documents the methods and data used in the development of these relationships.

## 1.1 Opportune Landing Site program

The Opportune Landing Site (OLS) program, a joint industry/Department of Defense (DoD) initiative, is intended as a military planning tool to help select candidate landing sites, determine soil type, and infer the soil CBR to evaluate a site's potential to support military airlift operations. Within the OLS program, efforts are under way by Boeing to develop mapping software that uses commercially available Landsat imagery to remotely locate unimproved landing sites in natural terrain. Currently available Landsat imagery can identify areas that are sufficiently flat, and free of heavy vegetation, obstacles, and surface water, to allow airlift operations, soil and weather conditions permitting.

Once a potential site has been identified, the second module of the OLS program, also under development by Boeing, determines the soil type based on the pixilated satellite imagery and digital terrain elevation data (DTED).

Finally, under the third module of OLS software, the Cold Regions Research and Engineering Laboratory (CRREL) is using the Fast All-Seasons Soil State (FASST) model, with the inputs of soil type and measured or modeled weather data, to predict the soil moisture content and infer bearing capacity. Because the USAF design standard for airfields is based on bearing capacity expressed as CBR, any strength prediction must be converted to a CBR value for use in existing design methods. CBR is, in turn, used to evaluate the trafficability of the site by a specific aircraft. Together, the modules of the OLS program would eliminate or minimize the need for on-ground reconnaissance to locate potential landing sites before aircraft operations.

The OLS bearing capacity inference is based on a database of soils and their engineering properties from throughout the world (see Section 3). As the OLS program has developed, and as its soils database has been populated, it has became evident that several different types of testing and instrumentation have been used to determine soil bearing capacity. Before the development of the DCP, the two most common methods, especially for the U.S. Army Corps of Engineers (USACE) and USAF, were field CBR and cone penetrometer. However, because of the difficulty of the CBR field test, the amount of CI soil strength data outnumbers the amount of field CBR data 26 to 1 in the OLS database. Therefore, several different efforts are under way to provide a more diverse set of CBR values for global soils.

## 1.2 Scope

As a complement to the work of Semen (2006) and others in providing the greatest amount and variety of CBR data for use in the OLS program, this report focuses on the determination of a correlation between CBR and CI to access the large amount of historic CI data available. Also, as the U.S. Army routinely uses the vehicle trafficability cone penetrometer for soils evaluation, the OLS database will continue to grow, and for that data to be usable for airfield evaluation, a well-documented and robust CBR versus CI correlation is needed. The goal of this work is to document existing and improved CBR and CI correlations and to provide a database of soil strength values, and also a correlation—by soil type—of CBR values to CI values for use in the contingency airfield site selection process within the OLS program.

# 2 Background

## 2.1 CBR test

The CBR test was originally developed by O. J. Porter for the California Highway Department during the 1920s. It is a load-deformation test performed in the laboratory or field; results are then used with empirical design charts to determine the thickness of flexible pavement, base, and other layers for a given vehicle loading. Though the test originated in California, the California Department of Transportation and most other highway agencies have abandoned the CBR method of pavement design for the Hveem stabilometer and other methods (Oglesby and Hicks 1982). In the 1940s, USACE adopted the CBR method of design for flexible airfield pavements and USACE and USAF design practice for surfaced and unsurfaced airfields is still based on CBR today (U.S. Army and Air Force 1994b).

CBR may be performed either in the laboratory, typically with a recompacted sample, or in the field. The laboratory CBR test method is defined by ASTM D 1883-05 (American Society for Testing and Materials 2005). Because of typical logistical and time constraints, the laboratory test does not lend itself to use for contingency road and airfield design. In-situ CBR tests are also time-consuming to run and are usually impractical for use in theater (U.S. Army and Air Force 1994b). To address the concerns with the standard CBR tests, the military has adopted other tools more suited for field operations. The airfield cone penetrometer and the dual mass DCP are most typically used in the field, and correlations are provided to translate their measurements into CBR values for use in design (U.S. Army and Air Force 1994b). Historically, however, there is a great deal of directly measured field CBR information available.

The field CBR test procedure is described in ASTM D 4429-04 (American Society for Testing and Materials 2004) and Army FM 5-530 (U.S. Army, Air Force, and Navy 1987). The field CBR test is performed by measuring the penetration resistance of a 1.954-in.-diameter (3-in.$^2$ end area) cylindrical steel piston advanced into the soil at a rate of 0.05 in./min. The reaction force is measured, by means of a calibrated proving ring, at increments of 0.025 in. until a total penetration of 0.500 in. is reached.

To determine the CBR value, the reaction forces measured at 0.100- and 0.200-in. penetration are compared to standardized values of 1,000 and 1,500 pounds per square inch (psi), respectively. These represent the resistance of a high-quality, well-graded crushed limestone gravel with ¾-in. maximum aggregate-sized particles. The values of two forces measured in the test are divided by their respective standardized value, and then multiplied by 100, to yield two index values. The larger of the two values is reported as the CBR of the soil, in percent.

The CBR test method is most appropriate and gives the most reliable results for fine-grained soils. It can also be used to characterize the strength of soil-aggregate mixtures (e.g., subbases) and unbound aggregate base courses. In cohesionless soils, especially ones that include large particles, the reproducibility of the test is poor (Rollings and Rollings 1996). In the laboratory test procedure, test samples are prepared with soils of aggregate particle size of less than ¾ in. In the case of soils where particle sizes greater than ¾ in. exist, the large particles are removed from the sample and replaced with an equal mass of material that falls between the ¾-in. sieve and the number 4 (4.75-mm) sieve sizes. In the field CBR test procedure, removal of larger particles that may adversely affect the test results is not possible, and therefore these types of soils are likely to produce unreliable results.

## 2.2 CBR prediction

There are several existing methods for predicting CBR values for soils based on soil classification, soil characteristics, and soil index test values. Semen (2006) discusses several approaches to CBR prediction:

- CBR values by soil type based on the USCS. From the literature, Semen summarized CBR values based on the specific soil type as defined by the USCS as shown in Table 1. Letter symbols for the USCS soils designations are defined in Table 2. The relationship between CBR and USCS soil classification is schematically displayed in Figure 1 (Fang 1991).

- Mechanistic-Empirical Design for New and Rehabilitated Pavement Structures as developed under the National Cooperative Highway Research Program (NCHRP) (2004) uses a simple regression to predict CBR based on grain-size characteristics for non-plastic soils, and grain size and plasticity index for plastic soils.

- Soil strength “signature” concept combines laboratory results from CBR and standard moisture-density tests (known as Proctor curves) to provide a relation between CBR, compaction, and molded moisture content (Rada et al. 1989).

Table 1. CBR by soil type from Semen (2006).

| USCS Soil Type | U.S. Army Corps of Engineers (1960), U.S. Army (1997), and U.S. Army and Air Force (1983) | Yoder and Witczak (1975) | U.S. Army, Air Force and Navy (1987), and Portland Cement Association (1992) | Rollings and Rollings (1996) | National Cooperative Highway Research Program (2004) |
|---|---|---|---|---|---|
| GW | 40–80 | 60–80 | 60–80 | 60–80 | 60–80 |
| GP | 30–60 | 35–60 | 25–60 | 35–60 | 35–60 |
| GM | 20–60 | 40–80 | 20–80 | 40–80 | 30–80 |
| GC | 20–40 | 20–40 | 20–40 | 20–40 | 15–40 |
| SW | 20–40 | 20–40 | 20–40 | 20–50 | 20–40 |
| SP | 10–40 | 15–25 | 10–25 | 10–25 | 15–30 |
| SM | 10–40 | 20–40 | 10–40 | 20–40 | 20–40 |
| SC | 5–20 | 10–20 | 10–20 | 10–20 | 10–20 |
| ML | 15 or less | 5–15 | 5–15 | 5–15 | 8–16 |
| CL | 15 or less | 5–15 | 5–15 | 5–15 | 5–15 |
| OL | 5 or less | 4–8 | 4–8 | 4–8 | — |
| MH | 10 or less | 4–8 | 4–8 | 4–8 | 2–8 |
| CH | 15 or less | 3–5 | 3–5 | 3–5 | 1–5 |
| OH | 5 or less | 3–5 | 3–5 | 3–5 | — |
| Pt | — | — | — | <1 | — |
| CL-ML | — | — | — | — | — |
| GW-GM | — | — | — | — | 35–70 |
| GW-GC | — | — | — | — | 20–60 |
| GP-GM | — | — | — | — | 25–60 |
| GP-GC | — | — | — | — | 20–50 |
| GC-GM | — | — | — | — | — |
| SW-SM | — | — | — | — | 15–30 |
| SW-SC | — | — | — | — | 10–25 |
| SP-SM | — | — | — | — | 15–30 |
| SP-SC | — | — | — | — | 10–25 |
| SC-SM | — | — | — | — | — |

Table 2. Letter symbols in the USCS (American Society for Testing and Materials 1985).

| Soil Groups (First Letter) | Symbol |
|---|---|
| Gravel | G |
| Sand | S |
| Silt | M |
| Clay | C |
| Soil Characteristics (Second Letter) | Symbol |
| Well graded | W |
| Poorly graded | P |
| Low plasticity (liquid limit under 50) | L |
| High plasticity (liquid limit over 50) | H |
| Organic (silts and clays) | O |
| Organic (peat) | Pt |

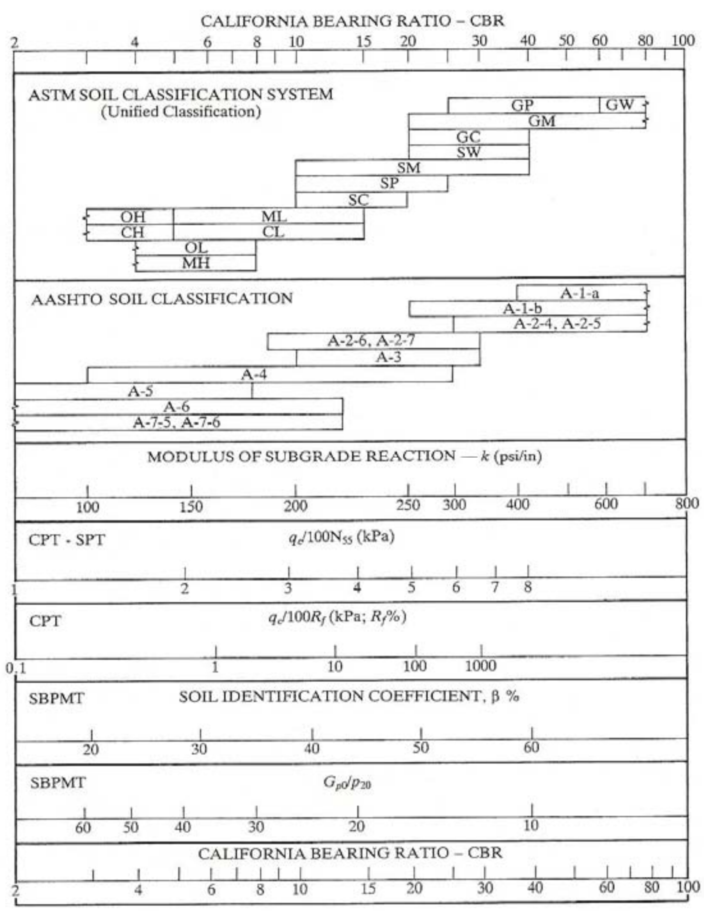


Figure 1. Relationships between CBR, USCS, and American Association of State Highway and Transportation Officials (ASSHTO) soil classification, and other soil parameters (Fang 1991).

- Joint Rapid Airfield Construction (JRAC) program in progress is developing a prediction model for CBR based on moisture content and compaction levels, for different USCS soil types. This approach is also based on regression analysis (Berney 2008)

Semen (2006) also discusses several site-specific or specialized prediction models, where soils from a specific location or region have been sampled and tested to determine CBR relationships specific to those soils. The equations developed include terms for field dry density, moisture content, plasticity index, and liquid limit, among others. These approaches, though developed to work in specific locations, may also have application in a global database and prediction model.

## 2.3 Cone penetrometer tests

There are three types of cone penetrometers that are historically or currently used by the USACE and USAF for field testing with regard to soils trafficability and pavement design: (1) the trafficability penetrometer, (2) the airfield penetrometer, and (3) the dual mass-DCP.

The trafficability penetrometer is a handheld device with a dial-type load indicator and equipped with a choice of two sizes of 30° cones. The dial gauge for the Waterways Experiment Station (WES) cone penetrometer typically ranges from 0 to 300 and the numbers are often reported as unitless CI values or as pressure (pressure in psi can be read directly from the 0–300 dial gauge depending on the cone size and the proving ring calibration). The agriculture community typically reports CI values in pressure units of kPa.

The trafficability penetrometer is a simple probe-type instrument designed for quick and easy field use to obtain an index of soil strength. The use of the trafficability penetrometer is described in ASAE standard S313.2 (American Society of Agricultural Engineers 1985), SAE standard J939 (Society of Automotive Engineers 1967), U.S. Army TM 5-330 (U.S. Army 1968), and U.S. Army FM 5-430-00-1 and Air Force AFJP 32-8013 (U.S. Army and Air Force 1994a). The cone is pressed into the soil at a uniform rate of approximately 30 mm/s (1 in./sec). The first reading is taken when the base of the cone is flush with the soil, and then every 25–50 mm (1–2 in.) thereafter, depending on the application. The larger cone, with a base area of 0.5 in.$^2$ (323 mm$^2$), is used with soft soils and sands whereas the smaller cone, 0.2-in.$^2$ (130-mm$^2$) base area, is used for harder soils and soils with fines.

The airfield cone penetrometer, consisting of a 30° cone with a 0.2-in.$^2$ base area, has a range of 0–15 (CBR value of 0 to approximately 18). Similar in design to the trafficability penetrometer, airfield cone procedures are described in U.S. Army FM 5-430-00-1 and Air Force AFJP 32-8013 (U.S. Army and Air Force 1994a). Force is applied to the penetrometer at a rate of ½–1 in./sec, with readings taken at 2-in. increments, up to 24 in., or until a maximum reading of 15 is obtained. The 0-in. reading is discarded. Readings from the airfield cone penetrometer are reported as the airfield index (AI).

Readings from the 0.2-in.$^2$ cone trafficability penetrometer must be divided by 20 to obtain the AI; the reading obtained with the 0.5-in.$^2$ cone must be divided by 50 to obtain the AI (U.S. Army and Air Force 1994b).

The DCP is the current USAF standard for measurement of bearing strength for airfields. The use of the DCP is described in ASTM D 6951-03 (American Society for Testing and Materials 2003). The dual-mass DCP consists of a 5/8-in.-diameter steel rod with a steel cone attached to one end, which is driven into the soil by means of a sliding dual-mass hammer. The angle of the cone is 60°, and the diameter of the base of the cone is 0.79 in. The DCP is driven into the ground by dropping either a 17.6-lb or 10.1-lb sliding hammer from a height of 22.6 in. The cone penetration caused by one blow of the 17.6-lb hammer is essentially twice that caused by one blow of the 10.1-lb hammer, and is therefore preferred for high-strength soils. The depth of cone penetration is measured at selected penetration or hammer-drop intervals, and the soil shear strength is reported as the DCP index in millimeters/blow. The DCP index is entered into an empirical equation to get a corresponding CBR value for use in planning or design, as discussed in Section 2.4.6.

## 2.4 Existing correlations between CBR and CI

There have been few comprehensive studies to correlate CBR with CI, with either field or laboratory CBR data. However, beginning almost as early as the adoption of the CBR test by USACE in the 1940s, several studies have done at least some preliminary analysis of the relationship.

### 2.4.1 U.S. Army TM 3-240 on trafficability of soils

U.S. Army TM 3-240 (U.S. Army 1948) includes some consideration of the relationship between CBR and CI as incidental to the main focus of the report, which was to explore the effects of moisture content and density on the trafficability of soils, with heavy emphasis on the soils' plasticity. However, TM 3-240 does present both CI and CBR data for a number of different soil types and presents a composite plot of CBR versus CI as shown in Figure 2. Of these soils, Numbers 1, 2, 4, and 5 are non-plastic. Apart from these four, all but one (Number 11) of the remaining fine-grained soils appeared to share a linear relationship between CBR and CI with a similar slope, although the logarithmic plot obscures the wide disparity in the values, and none can be extrapolated through the origin. The authors of the TM concluded that there is no direct relationship of CBR to CI in non-plastic soils. (Note: Cross references for soil designations used in Figures 2 and 3 and Table 4 are given in Appendix A.)

### 2.4.2 Comparison of temperate and tropical soils

In a later study, whose purpose was to determine the similarity between tropical and temperate fine-grained, plastic soils with regard to trafficability characteristics, Meyer (1966) created a similar family of curves for these two classes of soils. These plots, based on visual straight-line fit to the data, are given in Figure 3 along with the average for each of the two plots. Meyer concluded that there is no significant difference in the relationship between CI and CBR for tropical and temperate soils.

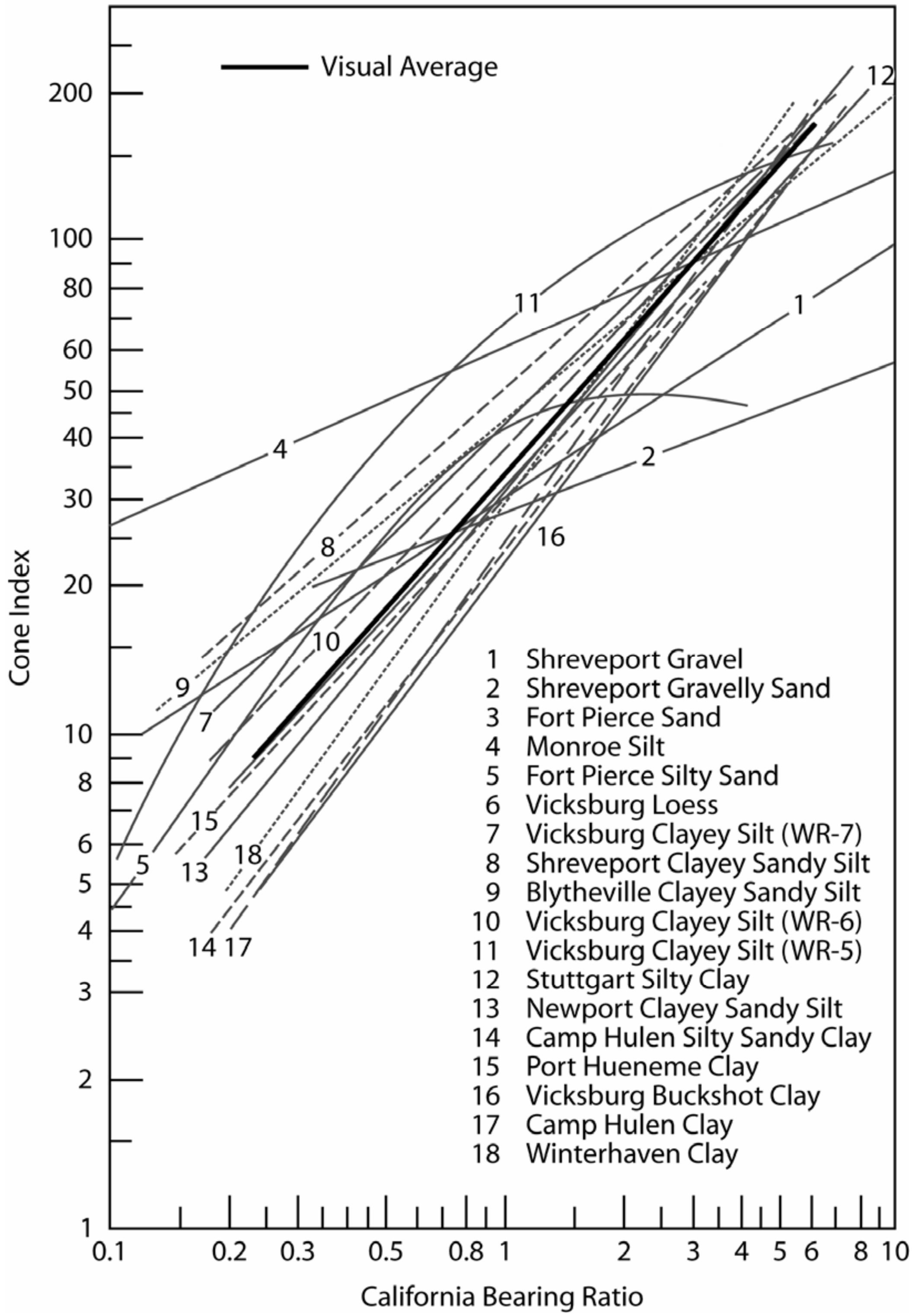


Figure 2. CI versus CBR (U.S. Army 1948).

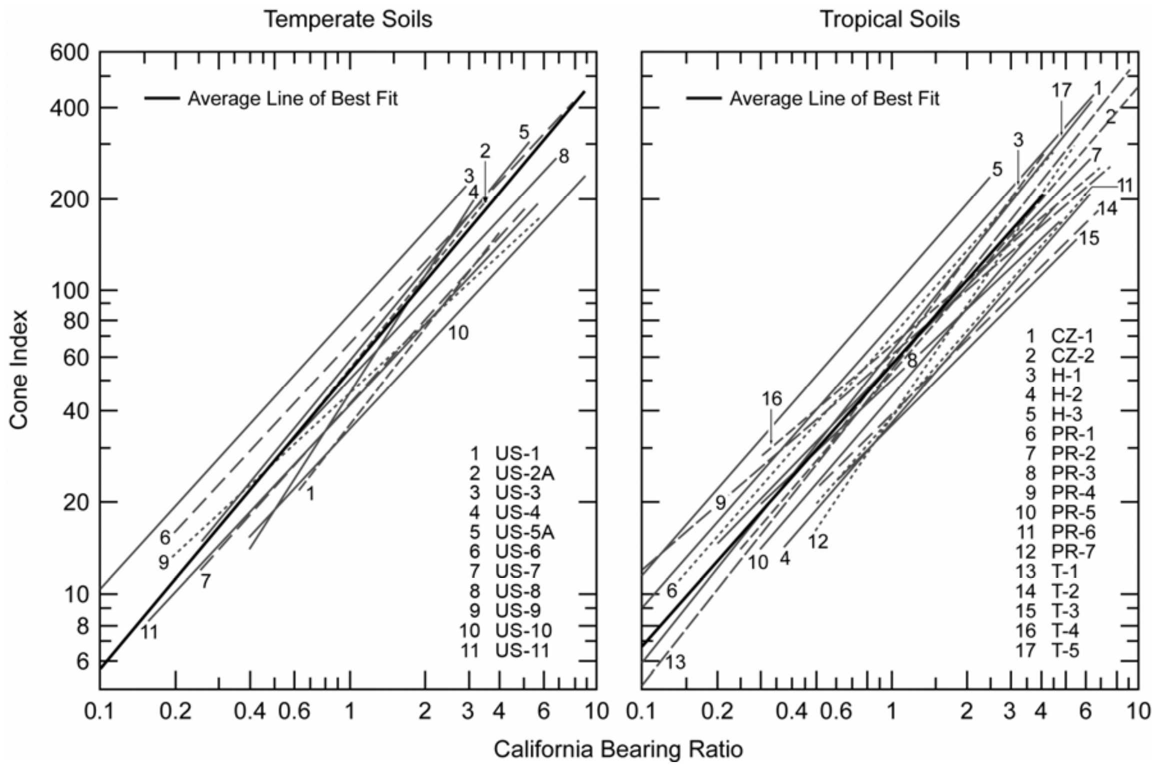


Figure 3. CI versus CBR for temperate and tropical soils (Meyer 1966).

### 2.4.3 Helicopter movement on unimproved terrain

Rush and Green (1974) plotted the data used in the above two studies, with additional data of their own, for their work with helicopter operations on unimproved surfaces. To this plot, shown in Figure 4, they added an upper boundary curve and a widely used correlation function between CI and CBR originally presented in TM 5-330 (U.S. Army 1968) (discussed in Section 2.4.5). Frankenstein (2005) fit equations to these correlations, labeled “Approximate Upper Boundary” and “Curve from US Army, 1968”, defining them as

Approximate upper boundary:

$$CBR = 0.00003\, CI^2 + 0.0315\, CI + 0.5916$$

Curve from U.S. Army (1968):

$$CBR = 0.00002\, CI^2 + 0.006\, CI + 0.129\,.$$

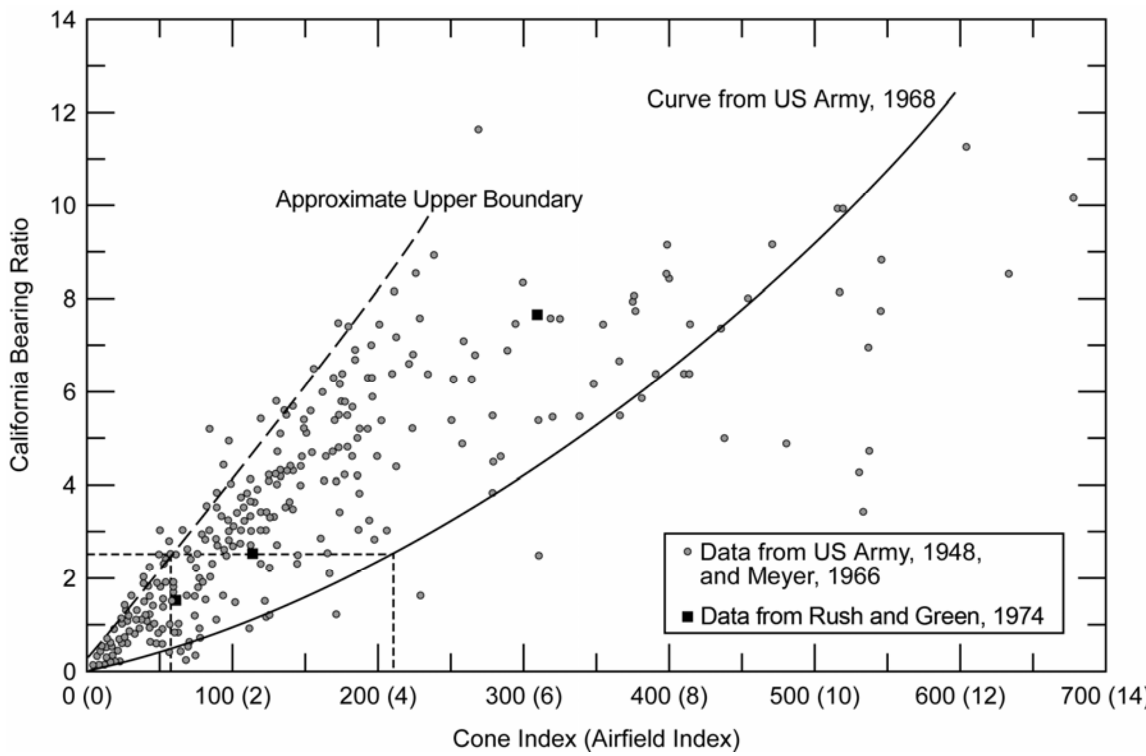


Figure 4. CBR versus CI (AI) (Rush and Green 1974).

### 2.4.4 Boeing/WES mobility test for transporter tires

In a project to test the performance of transporter tires in various conditions, Willoughby and May (1981) measured a number of physical and engineering properties of a limited number of soil types. With regard to CBR, they concluded

$$CBR \cong CI/20 \text{ (for clay soils with high plasticity);}$$

$$CBR \cong CI/50 \text{ (for less plastic silts and clays);}$$

$$CBR \cong CI/70 \text{ (for essentially non-plastic soils).}$$

In a plot shown in Figure 5, CBR data are plotted against CI data, giving a best linear fit of $CBR = CI/25$. However, this relationship becomes $CBR = CI/70$ if it is calculated including CBR values derived from DCP measurements that were also collected at the same sites and plotted against both CI and CBR.

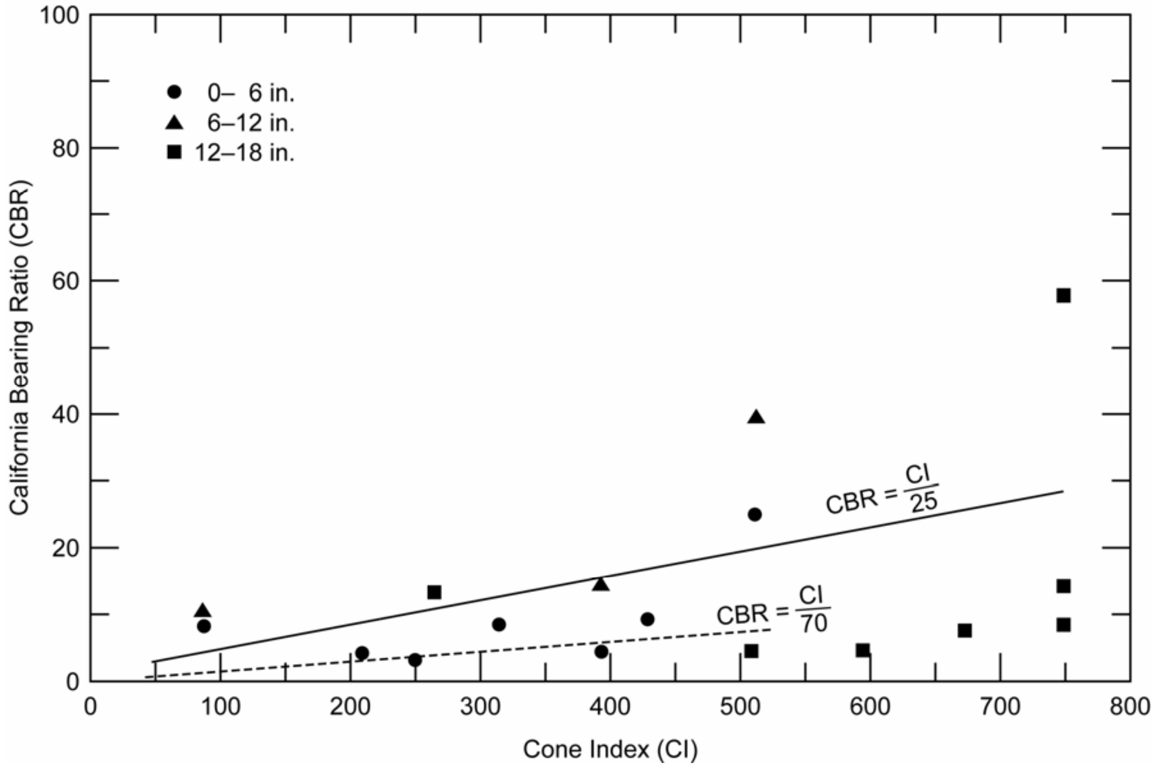


Figure 5. CBR versus CI (Willoughby and May 1981).

### 2.4.5 FM 5-410 on military soils engineering

FM 5-410 on military soils engineering (U.S. Army 1997) gives an overview of soil properties and testing procedures, including CBR, as well as how it relates to the AI, which is occasionally referred to in other sources. Figure 6 indicates the correlation between CBR and AI that originally came from TM 5-330 (U.S. Army 1968) and was presented in the graph by Rush and Green (1974) shown in Figure 4. FM 5-410 recommends this correlation for planning and design use.

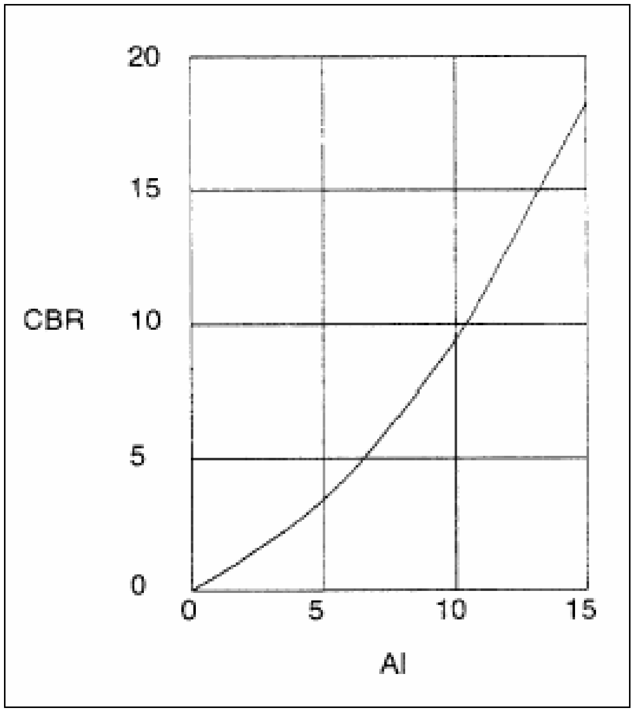


Figure 6. Correlation of CBR and AI (FM 5-410) (U.S. Army 1997).

In addition to the graph, FM 5-410 offers tables of soil characteristics pertinent to road and airfield design. CBR data from that table are given in Table 1 (data under heading that references U.S. Army 1997).

### 2.4.6 FM 5-430-00-2 airfield and heliport design

FM 5-430-00-2, *Planning and design of roads, airfields, and heliports in the theater of operations—airfield and heliport design*, Vol. II (U.S. Army and Air Force 1994b), duplicates Figure 6 above from FM 5-410. It also adds an additional relationship for CBR versus DCP index, shown in Figure 7. The use of the DCP and the correlation provided in Figure 7 are part of the current official guidance for determining CBR for planning and design, and are under use by the USAF for contingency airfields within theater. The U.S. Army does not currently have the DCP in its testing inventory (U.S. Army and Air Force 1994b).

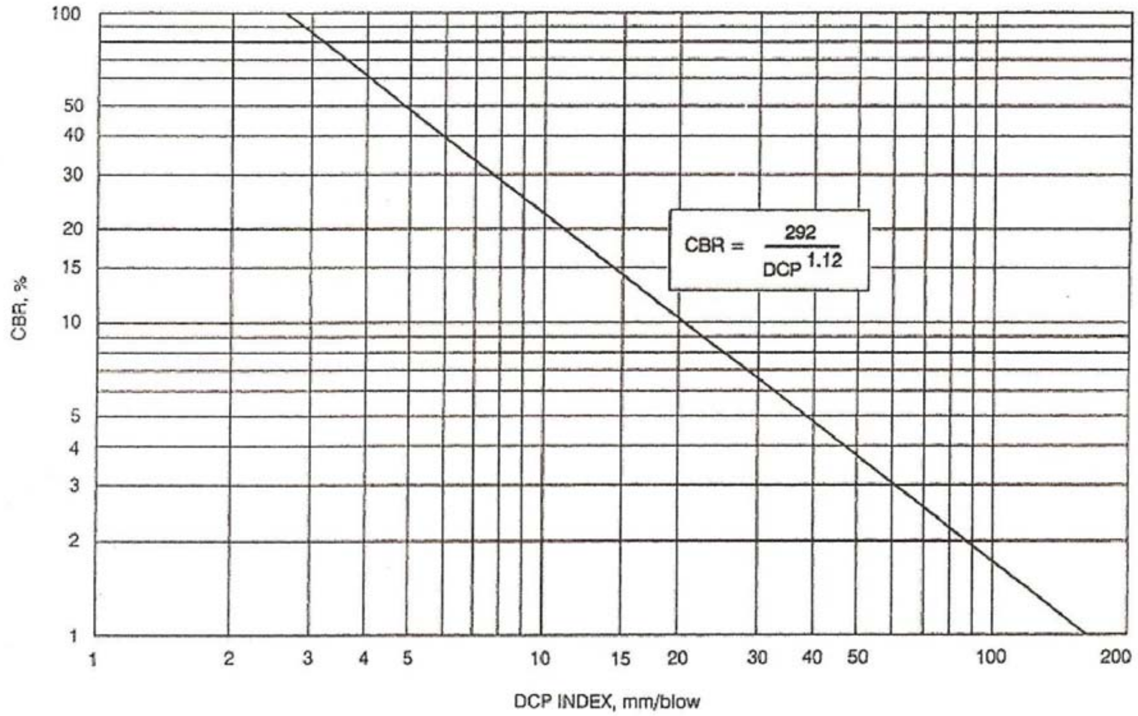


Figure 7. Correlation of CBR versus DCP index (U.S. Army and Air Force 1994b).

# 3 Database

The OLS soils database was designed to represent a global range of soil types to allow evaluation of any potential landing site, regardless of location (Seman and Shoop 2007; Shoop et al. 2008a). This database was used to generate relationships between soil physical characteristics and CBR strength (Semen 2006; Seman 2008; Shoop et al. 2008b). The cone index portion of the OLS soil strength database is fully described in Diemand et al. (2008). The rationale for selection of data to populate the database included the following objectives and restraints (from Semen 2006):

1. Incorporate as many of the 26 USCS soil types into the database as possible.

2. Ensure the database is representative of the relative prevalence of the USCS soil types worldwide. The data should reflect the probability of encountering a given soil type and the variability within some of the more common soil types.

3. Focus on geotechnical parameters, especially those used to characterize engineering behavior of soils in the civil engineering community.

4. Concentrate on records that contain field CBR measurements, primarily, and for the purposes of this report, corresponding CI measurements.

5. Make sure that the data encompass the range of conditions that would be found in naturally deposited soils, both those that have been selected for construction, and those that are unfit for construction or use as contingency airfields. The OLS program must be able to select or reject sites on the basis of soil bearing capacity.

6. Incorporate as much geographic, geologic, environmental, and dispositional diversity as possible to reflect the wide variety of conditions under which natural soils can form.

7. Bring together a consistent and well-documented dataset populated with standardized test method results and parameters. Ensuring that individual data records are referenced to their proper source is useful in several respects: any peculiar soil can be isolated and dealt with separately, if needed; further information may be collected and added from the source to support future efforts; and inferences due to test locations or seasonal variation may be possible.

The CI database, with 14,574 entries, came from several different sources as discussed by Diemand et al. (2008). The subset database used for correlation between CBR and CI is much smaller, and came from three sources: Meyer (1966), U.S. Army (1948), and Willoughby and May (1981). The CI database includes 562 entries that have both field CBR and CI measurements.

## 3.1 Database field description

A total of 62 fields were identified to store information about identification, reference source, site description, soil classification, physical properties, strength index testing (both laboratory and field), particle size and shape, and remarks. Table 3 lists the OLS database field identifiers. The contents of each of these fields is described in further detail in Appendix B. The CI database uses the same field descriptors as the OLS database.

## 3.2 Geographic and soil type distribution

The data used for the CBR versus CI correlation came from 42 separate test sites, shown in Table 4. The number of cases is listed for each site. These sites include 462 from within the continental United States, 55 from Puerto Rico, 32 from Thailand, and 13 from Panama. They encompass a broad range of geologic and environmental conditions, such as arid deserts, humid tropics, glacial till, coral islands, alluvial plains, volcanic deposits, dry lakebeds, and frost-active areas.

Table 3. Fields in the OLS soils databases.

| | |
|---|---|
| OLS Data Point # | Dry Density (laboratory) |
| JRAC Soil # | Optimum Moisture Content and Maximum Density |
| Test or Sample Date | Unsoaked CBR (laboratory) |
| Report # | Soaked CBR (laboratory) |
| Report Date | Moisture Content as Tested (weight %) |
| Report Title | Moisture Content as Tested (volumetric %) |
| Country Code (ISO-3166) | Trafficability Cone Index |
| Location | Remolding Index |
| Test Station | DCP Index (dynamic cone penetrometer) |
| Latitude | Field CBR |
| Longitude | Field Dry Density |
| Landform | Field Wet Density |
| Lithology of Parent Material | 3/4-inch Sieve, Maximum Percent Passing |
| Deposition Type | 3/4-inch Sieve, Minimum Percent Passing |
| Depth to Water Table | 3/8-inch Sieve, Maximum Percent Passing |
| Soil Type, USCS | 3/8-inch Sieve, Minimum Percent Passing |
| Alternate Soil Type | # 4 Sieve, Percent Passing |
| Alternate Soil System | # 10 Sieve, Percent Passing |
| Soil Description | # 40 Sieve, Percent Passing |
| Clay Mineralogy | # 100 Sieve, Percent Passing |
| Specific Gravity | # 200 Sieve, Percent Passing |
| Sample Depth Below Grade | Clay, Percent |
| Plastic or Non-Plastic | Roundness, Gravel |
| Liquid Limit (LL) | Roundness, Sand |
| Plastic Limit (PL) | Sphericity, Gravel |
| Plasticity Index (PI) | Sphericity, Sand |
| Compactive Effort | Remarks |
| Molding Moisture Content | |

Table 4. Number of cases in CI database CBR subset by test location.

| Location | Country | CBR and CI Cases |
|---|---|---|
| Bang Khen | Thailand | 7 |
| Barcelometa | Puerto Rico | 9 |
| Barksdale Army Airfield, Shreveport, LA | United States | 21 |
| Blythville Army Airfield, Blythville, AR | United States | 15 |
| Camp Huelen, Palacios, TX | United States | 49 |
| Chanthaburi | Thailand | 6 |
| Chieng Mai | Thailand | 5 |
| Clayton, GA | United States | 11 |
| Corozal | Puerto Rico | 9 |
| Corvallis, OR | United States | 8 |
| Delta, LA | United States | 40 |
| Fort Kobbe | Panama | 6 |
| Fort Pierce, FL | United States | 45 |
| Guanica | Puerto Rico | 9 |
| Jackass Flats Test Site, NV | United States | 9 |
| Khon Kaen | Thailand | 6 |
| Laurel, MS | United States | 11 |
| Lop Buri | Thailand | 8 |
| Mayaguez | Puerto Rico | 6 |
| Mound, LA | United States | 22 |
| Newport Army Airfield, Newport, AR | United States | 32 |
| Oxford, AL | United States | 7 |
| Pedro Miguel | Panama | 7 |
| Pomaria, SC | United States | 7 |
| Port Hueneme, CA | United States | 19 |
| Ramey | Puerto Rico | 7 |
| Roosevelt Roads Naval Station | Puerto Rico | 8 |
| Salisbury, NC | United States | 6 |
| Selmon Army Airfield, Monroe, LA | United States | 10 |
| Shaw, OR | United States | 6 |
| Shreveport, LA (Gifford Hill Sand & Gravel Co.) | United States | 15 |
| Shreveport, LA (Meriwether Supply Co. Gravel Pit) | United States | 10 |
| Stuttgart Army Airfield, Stuttgart, AR | United States | 22 |
| Tillamook, OR | United States | 8 |
| Vicksburg, MS | United States | 21 |
| Vicksburg, MS (Rifle Range) | United States | 16 |
| Vicksburg, MS (WES) | United States | 6 |
| Wahiawa, Oahu, HI | United States | 17 |

Table 4. Number of cases in CI database CBR subset by test location (cont'd).

| Location | Country | CBR and CI cases |
|---|---|---|
| Wainaku, HI | United States | 7 |
| Winterhaven, CA | United States | 22 |
| Yabucoa | Puerto Rico | 7 |
| Total | | 562 |

A summary of the USCS soil types contained in the CI database appears in Table 5.

Table 5. Distribution of USCS soil types in CI database.

| USCS Soil Classification | CBR and CI Cases |
|---|---|
| CH | 170 |
| CL | 174 |
| GP | 25 |
| MH | 95 |
| ML | 44 |
| SM | 49 |
| SP-SM | 5 |
| Total | 562 |

## 3.3 Statistical summary

Table 6 provides a statistical summary of the numeric soil property fields in the CI database that included significant amounts of unique data (i.e., none that were empty or contain data that do not vary between entries). Additional statistical information about the CI database is included in Appendix C.

One point of interest in the summary is the wide range of values for CI in the data. A maximum CI value of 926 was reported for one CL soil. However, subsequent refinement of the test method caps the CI value at 300 for vehicle trafficability, and 90 percent of the soils in the database have a CI value of 250 or less (see Figure 8). The higher CI values (greater than 300) were left in the database for the subsequent analysis because they also represented some of the higher CBR values for fine-grained soils. In addition, three data entries of CBR greater than 17 were reported, all for sandy gravels or gravelly sands. Because the field CBR and CI test methods are known to have difficulties with granular, cohesionless soils (i.e., penetration into a large particle may skew the value of CBR for the soil high), these data were excluded from the regression analysis.

Table 6. Statistical summary of numeric features in the CI dataset.

| Feature (Units) | Valid Cases | Quartiles | | | | | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|---|
| | | 0% | 25% | 50% | 75% | 100% | | |
| LL (%) | 11,006 | 10 | 34 | 59 | 82 | 454 | 66.9 | 48.6 |
| PL (%) | 10,873 | 10 | 22 | 33 | 51 | 302 | 42.9 | 33.6 |
| PI (%) | 10,872 | 1 | 10 | 19 | 34 | 176 | 24.3 | 20.3 |
| Specific gravity | 6,035 | 1.53 | 2.55 | 2.65 | 2.68 | 3.10 | 2.59 | 0.20 |
| Moisture content (wt. %) | 9,982 | 0.3 | 25.4 | 39.0 | 65.0 | 552.5 | 52.0 | 47.4 |
| Dry density (pcf) | 7,748 | 4.5 | 58.1 | 79.7 | 92.0 | 124.6 | 74.7 | 22.0 |
| CI | 13,980 | 1.0 | 103.0 | 155.0 | 254.0 | 926.0 | 212.9 | 179.8 |
| Field CBR | 562 | 0 | .5 | 1.95 | 4.82 | 116 | 3.4 | 7.1 |

# 4 Analysis

An initial attempt was made to find a single curve that would relate CBR to CI for all data similar to Rush and Green's analysis (Figure 4). It quickly became evident that a single algorithm could not be used for all soil types. In Figure 8 below, the upper limit of the Rush and Green (1974) data and the curve from TM 5-330 (U.S. Army 1968) are plotted along with the CBR versus CI data from the CI database by soil type, showing how several data in the database are outside the previously defined boundaries, especially for the coarser grained soils.

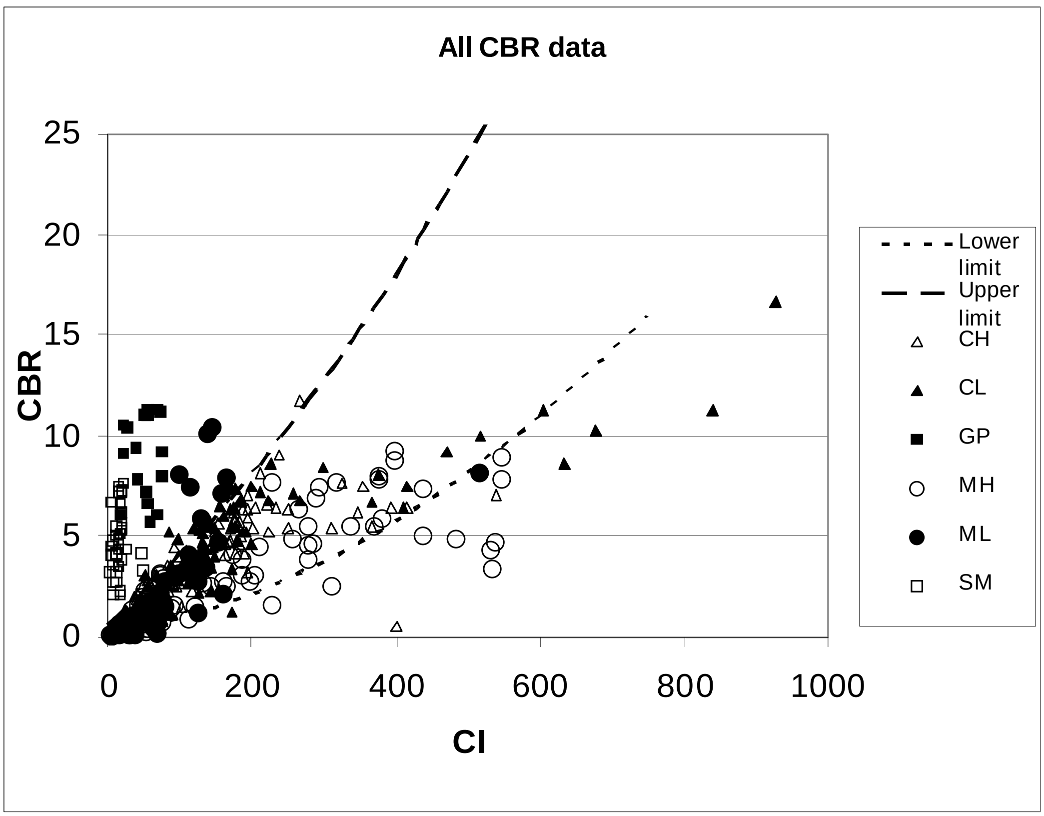


Figure 8. Correlation of CBR with CI by soil type. The upper limit shown is the upper limit from Rush and Green (1974) and the lower limit is the correlation from U.S. Army (1968) (same as in Figure 4).

## 4.1 First-, second-, and third-order equations

Because a universal equation relating CBR to CI regardless of soil type was not evident, analysis proceeded by soil type using first-, second-, and third-order equations. Figures 9–14 show the resulting regression equations and $R^2$ values. Although $R^2$ was quite good in some cases, particularly CL soils, curves with negative slopes were considered to be inappropriate, as logic indicates the CBR versus CI relationship should always have a positive slope.

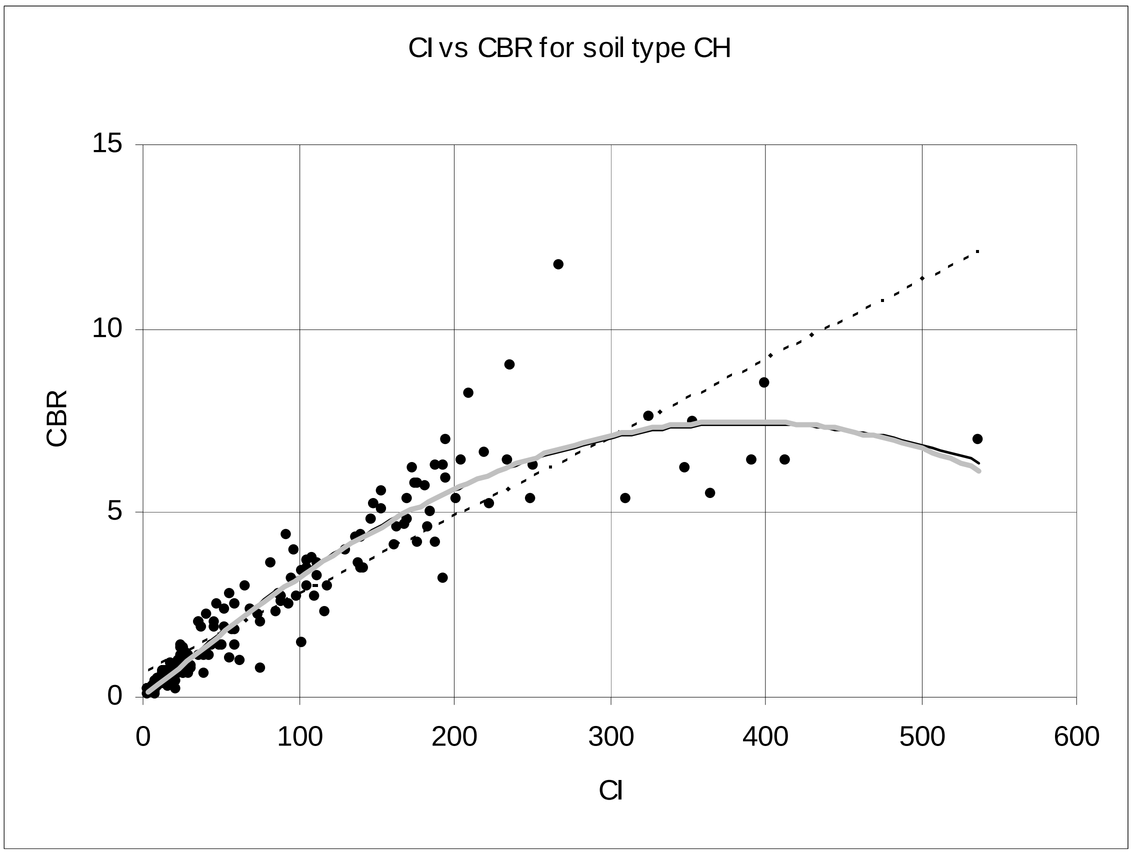


Figure 9. CBR versus CI for soil type CH.

(Grey line) $y = 3E\text{-}08x^3 - 7E\text{-}05^2 + 0.0421x - 0.1391$ $R^2 = 0.8436$

(Solid line) $y = -6E\text{-}05x^2 + 0.0394x - 0.0778$ $R^2 = 0.843$

(Dashed line) $y = 0.0197x + 0.7069$ $R^2 = 0.7136$

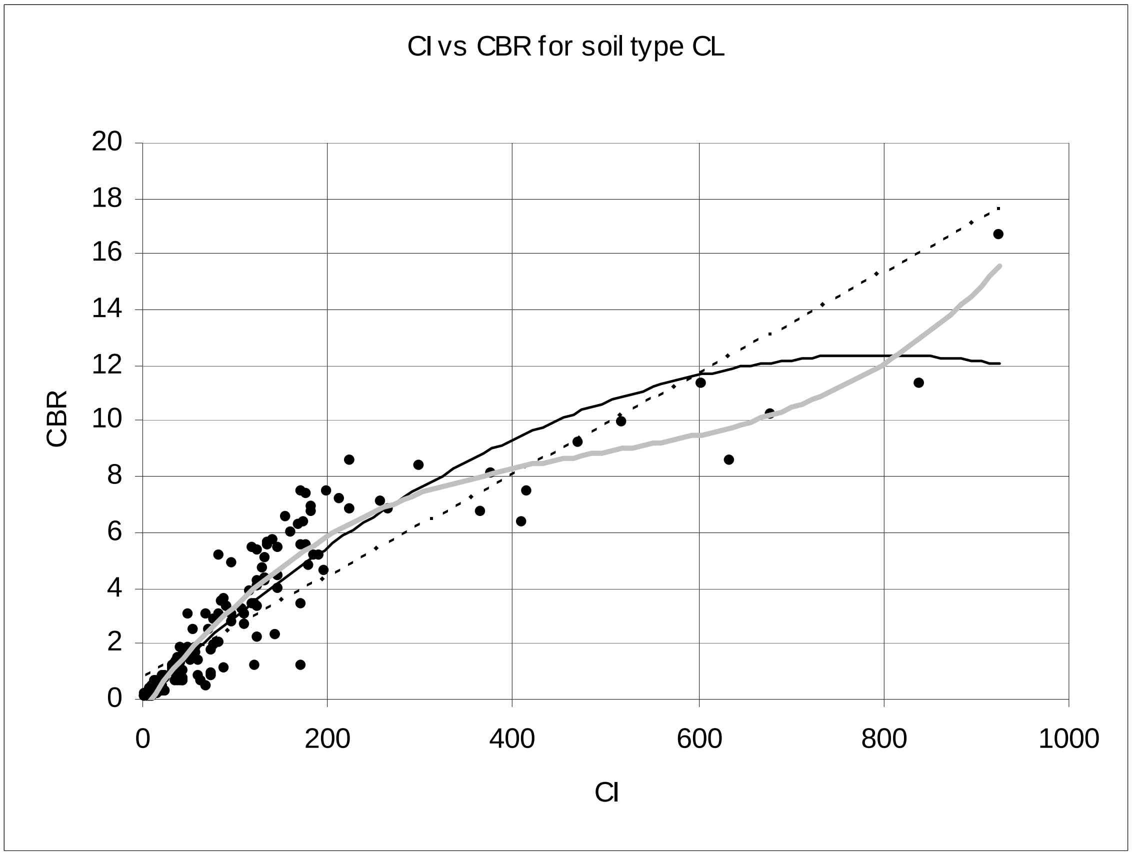


Figure 10. CBR versus CI for soil type CL.

(Grey line) $y = 5\text{E-}08x^3 - 8\text{E-}05x^2 + 0.045x - 0.3791$ $R^2 = 0.9084$

(Solid line) $y = -2\text{E-}05x^2 + 0.0309x + 0.0846$ $R^2 = 0.8734$

(Dashed line) $y = 0.0182x + 0.7844$ $R^2 = 0.8002$

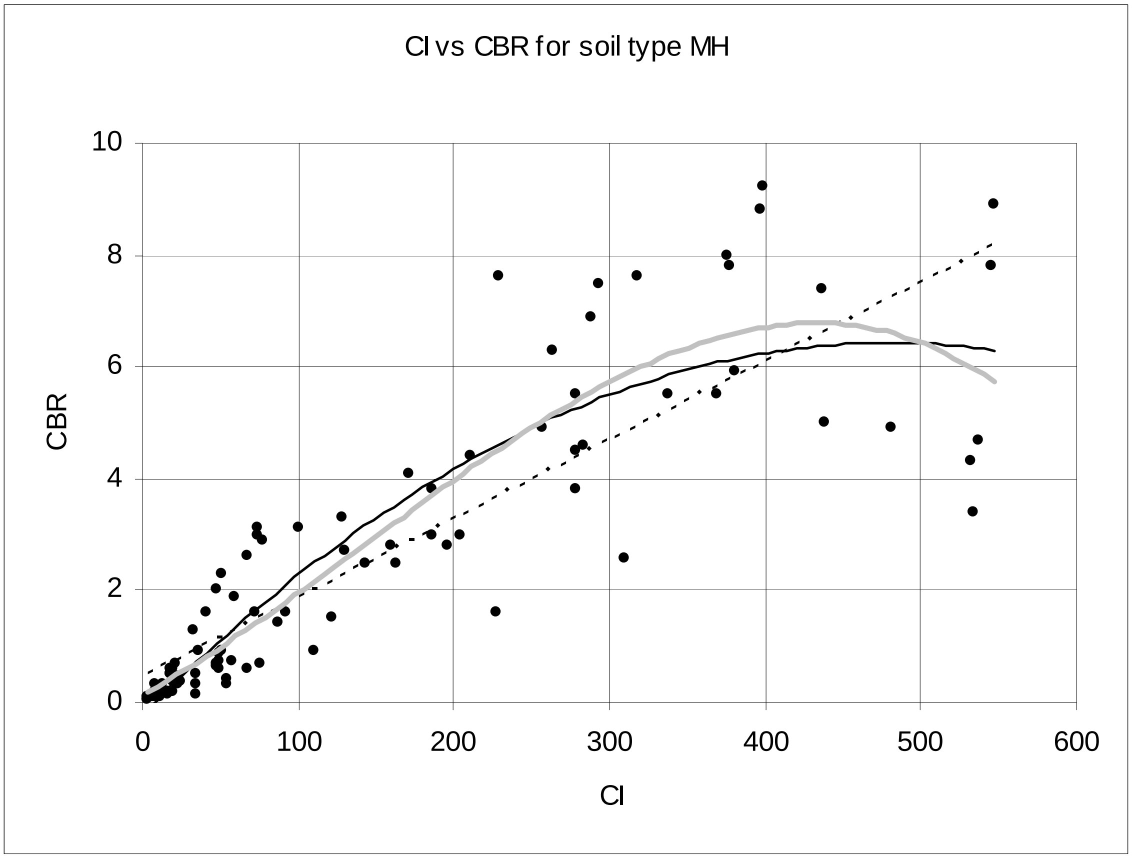


Figure 11. CBR versus CI for soil type MH.

(Grey line) $y = -8E\text{-}08x^3 + 4E\text{-}05x^2 + 0.0154x + 0.1368$ $R^2 = 0.816$

(Solid line) $y = -3E\text{-}05x^2 + 0.0277x - 0.2062$ $R^2 = 0.8064$

(Dashed line) $y = 0.0141x + 0.4641$ $R^2 = 0.7415$

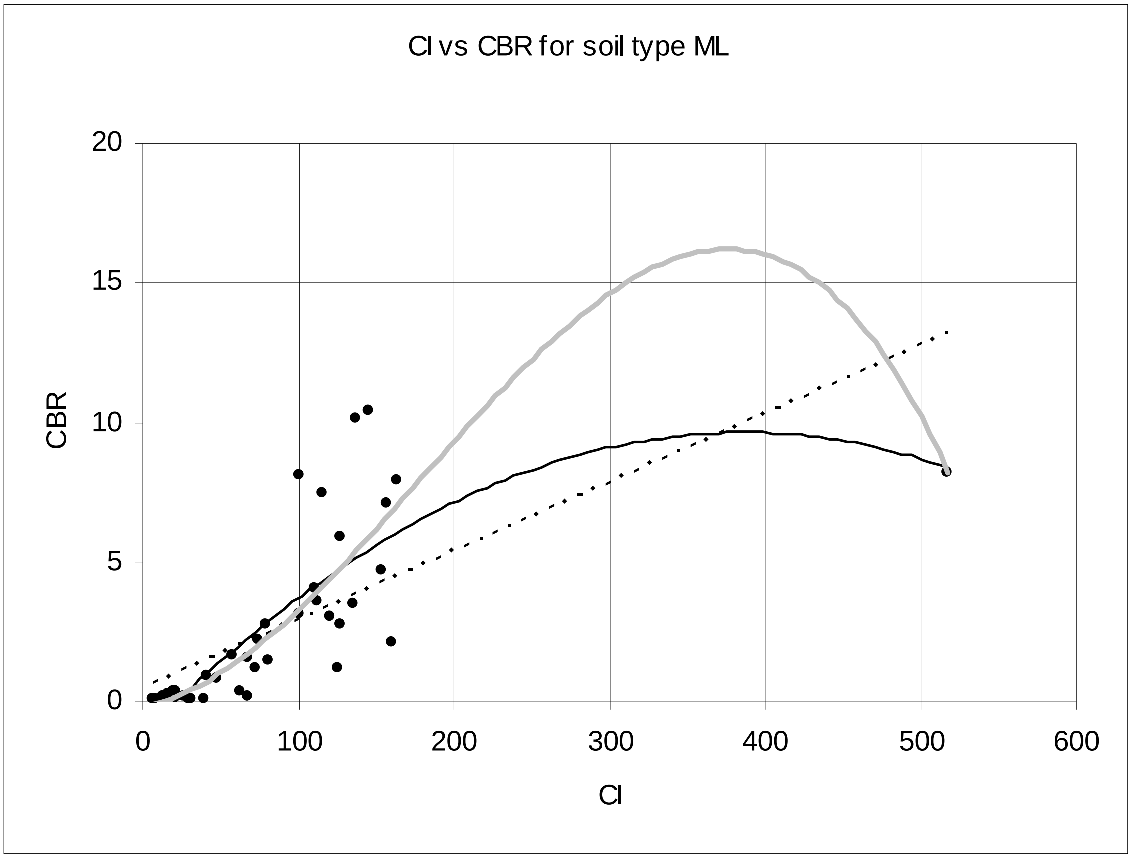


Figure 12. CBR versus CI for soil type ML.

(Grey line) $y = -5\text{E-}07x^3 + 0.0003x^2 + 0.0111x - 0.1772$ $R^2 = 0.6531$

(Solid line) $y = -7\text{E-}05x^2 + 0.0559x - 1.1516$ $R^2 = 0.6298$

(Dashed line) $y = 0.0244x + 0.4772$ $R^2 = 0.4609$

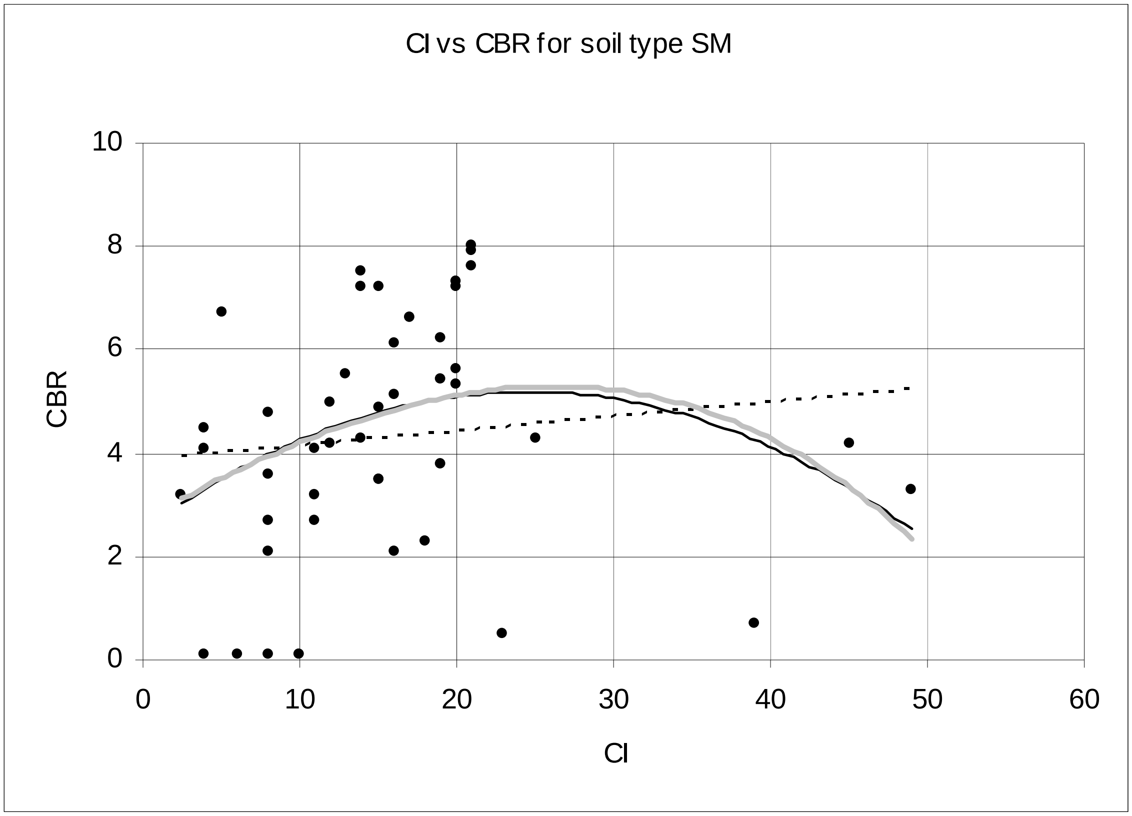


Figure 13. CBR versus CI for soil type SM.

(Grey line) $y = -4E\text{-}05x^3 - 0.0018x^2 + 0.1735x + 2.693$ $R^2 = 0.1072$

(Solid line) $y = -0.0044x^2 + 0.2175x + 2.5232$ $R^2 = 0.1066$

(Dashed line) $y = 0.0276x + 3.8841$ $R^2 = 0.0135$

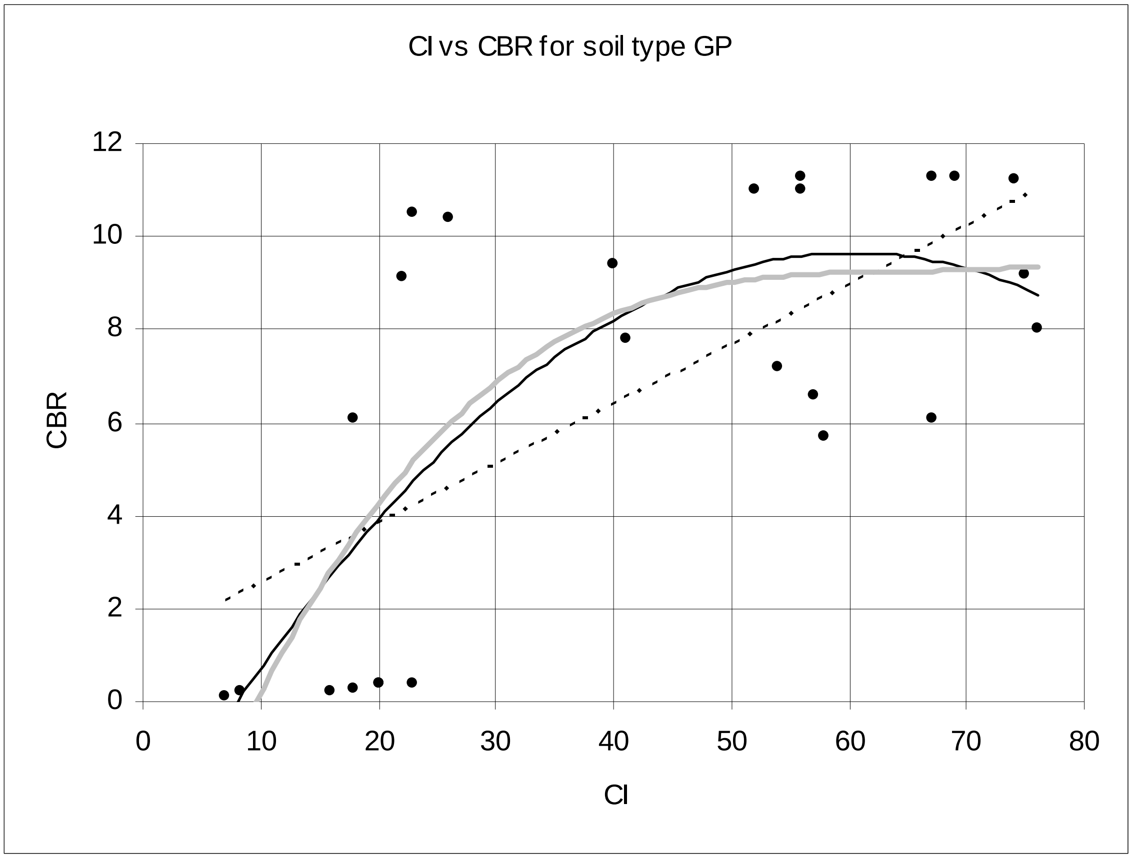


Figure 14. CBR versus CI for soil type GP.

(Grey line) $y = 5\text{E-}05x^3 - 0.0105x^2 + 0.6814x - 5.63$ $R^2 = 0.5564$

(Solid line) $y = -0.0035x^2 + 0.4271x - 3.209$ $R^2 = 0.547$

(Dashed line) $y = 0.1278x + 1.2753$ $R^2 = 0.4568$

## 4.2 Exponential equations

To eliminate the negative slope, data were analyzed using an exponential equation of the form:

$$y = a + bx^c \quad (1)$$

where:

$y$ = CBR
$x$ = CI.

Each soil was first analyzed separately and then subsets of data were analyzed by soil functional groupings. Subsets started with coarse-grained soils (SP-SM and GP), then proceeded to fine-grained soils (CH, CL, MH, and ML), and then high-plasticity (CH and MH) and low-plasticity (CL and ML) soils.

Figure 15 shows an example of this analysis for one soil type. The coefficients and $R^2$ values for the curves generated using this form of exponential equation are given in Table 7. The data plots are provided in Appendix D for all of the other soil types and soil subsets.

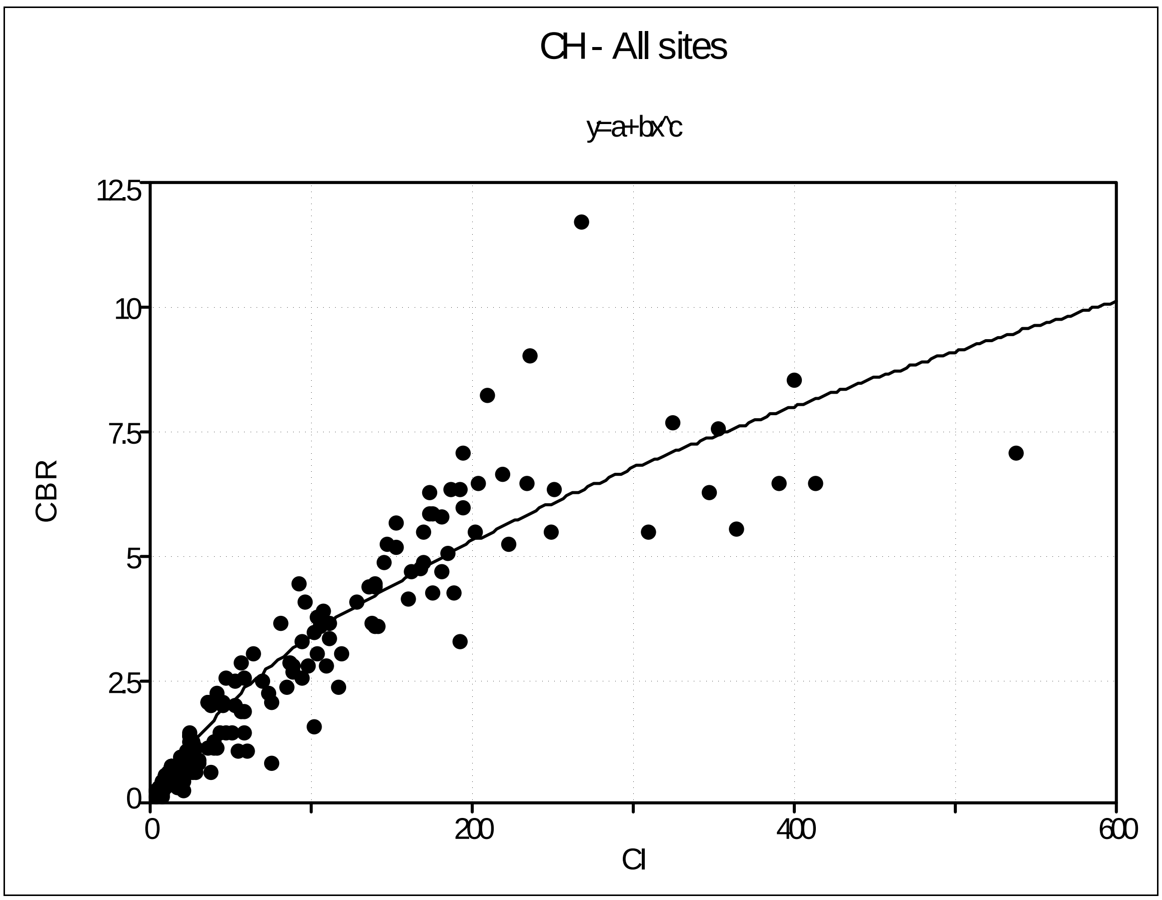


Figure 15. CBR versus CI for soil type CH.

Table 7. Coefficients for initial exponential equations.

| Soils Type | USCS Classification | Coefficients *a* | *b* | *c* | $R^2$ |
|---|---|---|---|---|---|
| | CH | –1.63462035 | 0.686080639 | 0.429374997 | 0.8035 |
| | CL | –1.22094966 | 0.368299769 | 0.545342184 | 0.8866 |
| | MH | –0.95392315 | 0.276153413 | 0.539104503 | 0.7808 |
| | ML | –3.14595803 | 0.928789277 | 0.430012159 | 0.5680 |
| | SM | –7.60469356 | 9.826607694 | 0.074386815 | 0.0612 |
| | GP | –31.4829214 | 24.68279433 | 0.121810957 | 0.5248 |
| | | | | | |
| Coarse-grained | SM + GP | 0.851525079 | 0.707683834 | 0.580775420 | 0.3500 |
| Fine-grained | CH, CL, MH, ML | –1.37924971 | 0.485100981 | 0.483650036 | 0.7725 |
| | | | | | |
| High plasticity | CH + MH | –1.76349771 | 0.757343985 | 0.399824150 | 0.7653 |
| Low plasticity | CL + ML | –1.48393600 | 0.438444720 | 0.522076596 | 0.8175 |

Although these curves represent a reasonably good statistical fit to the data, and do not have negative slopes, the decision was made to fit the equation through the origin because logic dictates that a soil with CBR equal to zero would also have a CI of zero.

Table 8 and Figures 16–26 are based on equations of the form:

$$y = ax^b \tag{2}$$

where:

$y$ = CBR
$x$ = CI.

Included are all soil types, the four soil subsets, and an “All soils” regression, in the order in which they are listed in Table 8.

Table 8. Coefficients for final exponential equations.

| Soils Type | USCS Classification | Coefficients | | |
|---|---|---|---|---|
| | | *a* | *b* | $R^2$ |
| | CH | 0.1264 | 0.6979 | 0.8516 |
| | CL | 0.1266 | 0.6986 | 0.8701 |
| | MH | 0.0820 | 0.7174 | 0.7715 |
| | ML | 0.1111 | 0.7390 | 0.5193 |
| | SM | 2.657 | 0.1859 | 0.0553 |
| | GP | 0.5009 | 0.7047 | 0.4803 |
| | | | | |
| Coarse-grained | SM + GP | 1.1392 | 0.4896 | 0.3495 |
| Fine-grained | CH, CL, MH, ML | 0.1305 | 0.6776 | 0.7724 |
| | | | | |
| High plasticity | CH + MH | 0.1460 | 0.6432 | 0.7741 |
| Low plasticity | CL + ML | 0.1281 | 0.6984 | 0.7962 |
| | | | | |
| All soils | | 0.2985 | 0.5358 | 0.4715 |

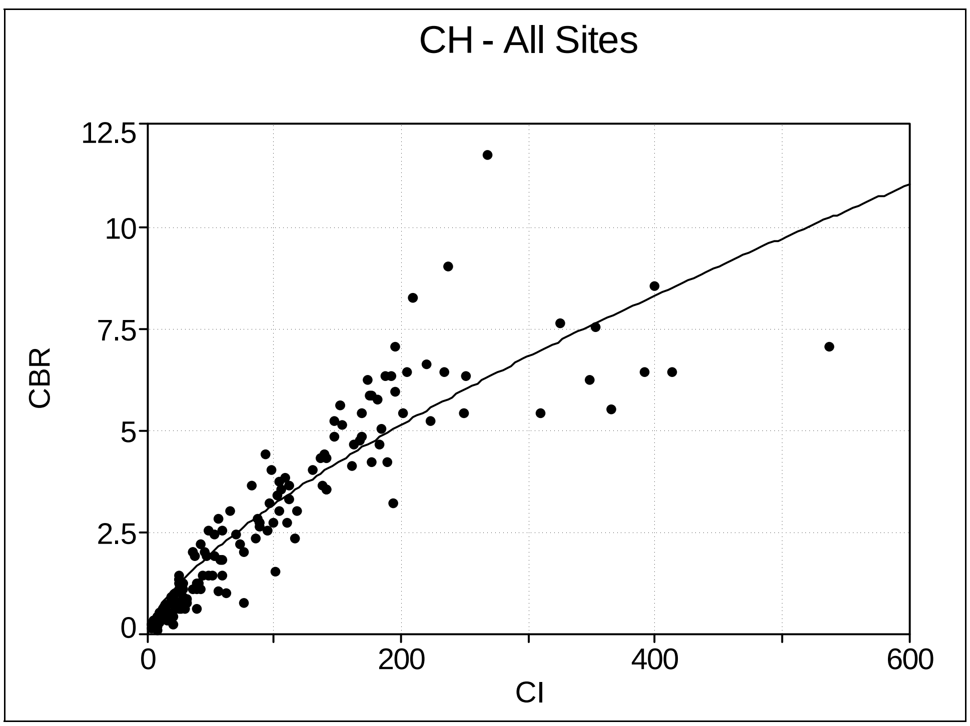


Figure 16. CBR versus CI for CH soils.

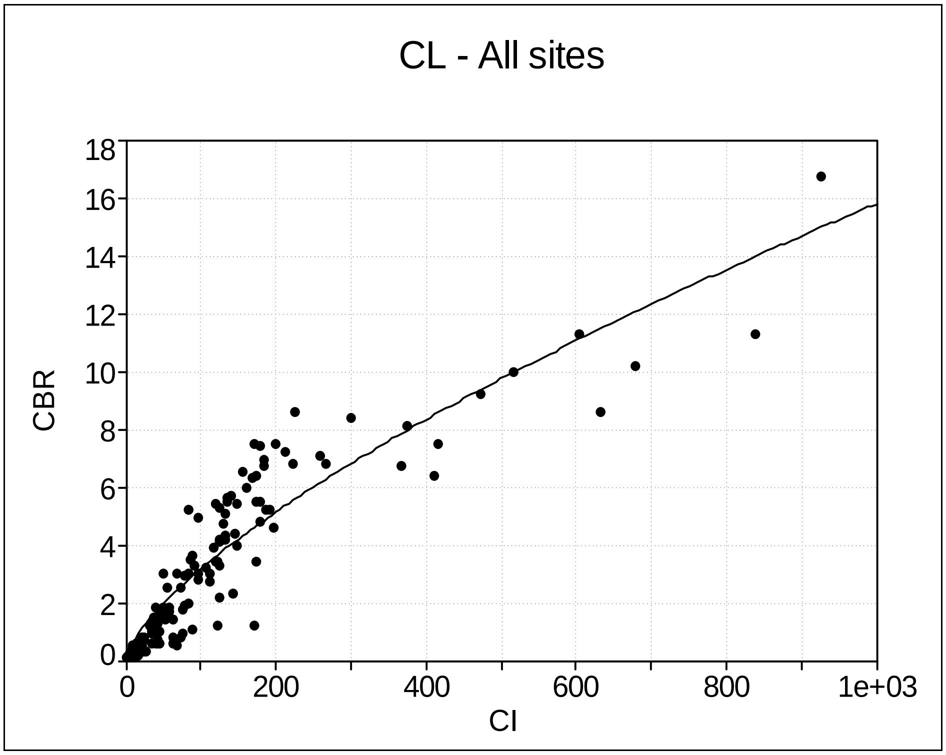


Figure 17. CBR versus CI for CL soils.

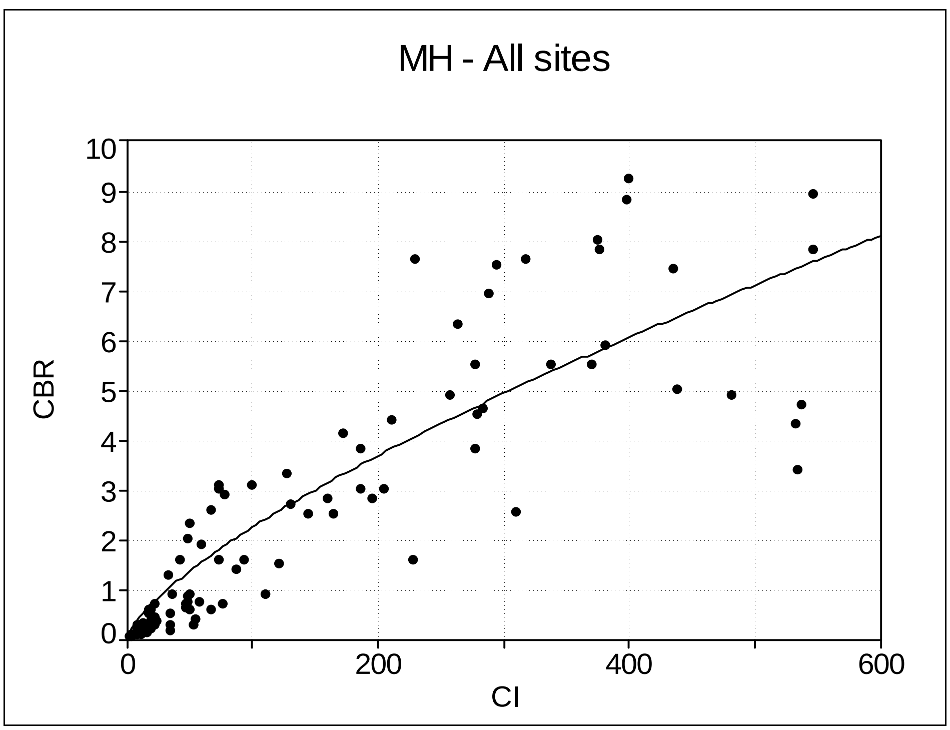


Figure 18. CBR versus CI for MH soils.

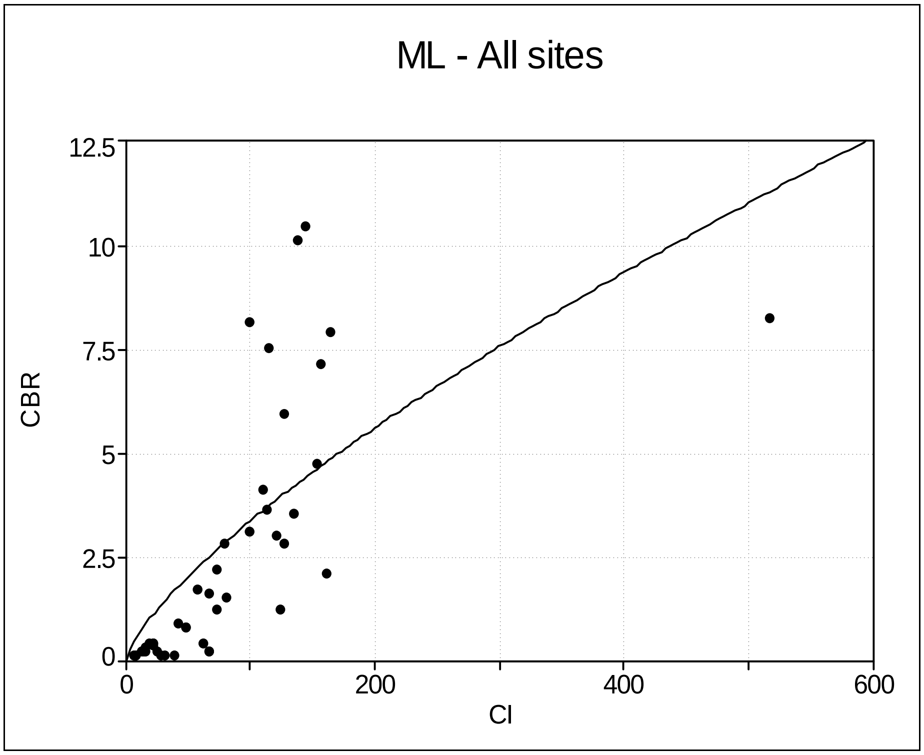


Figure 19. CBR versus CI for ML soils.

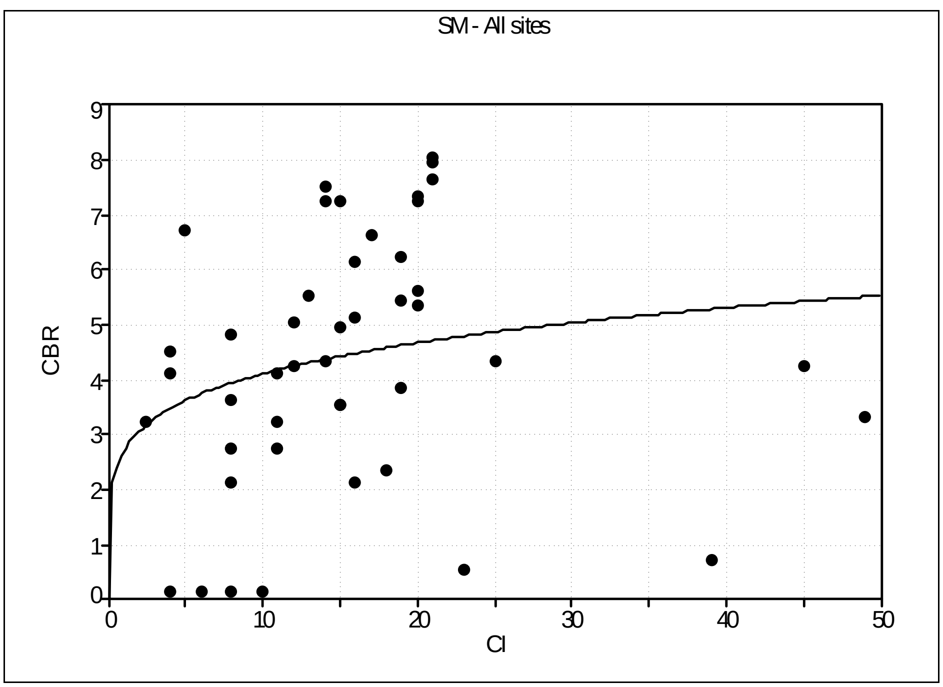


Figure 20. CBR versus CI for SM soils.

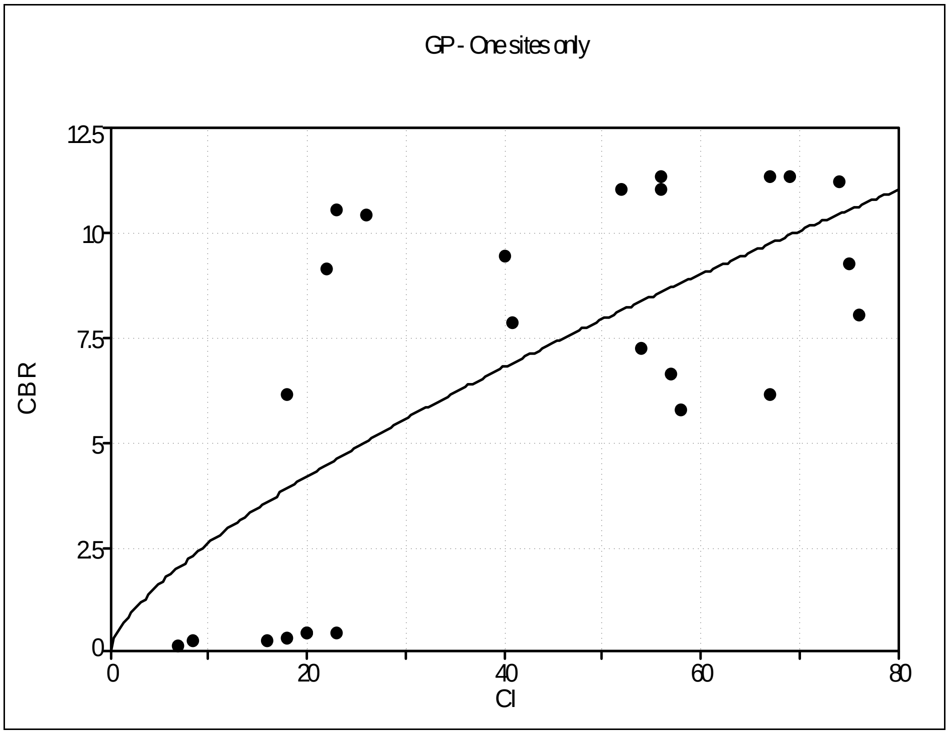


Figure 21. CBR versus CI for GP soils.

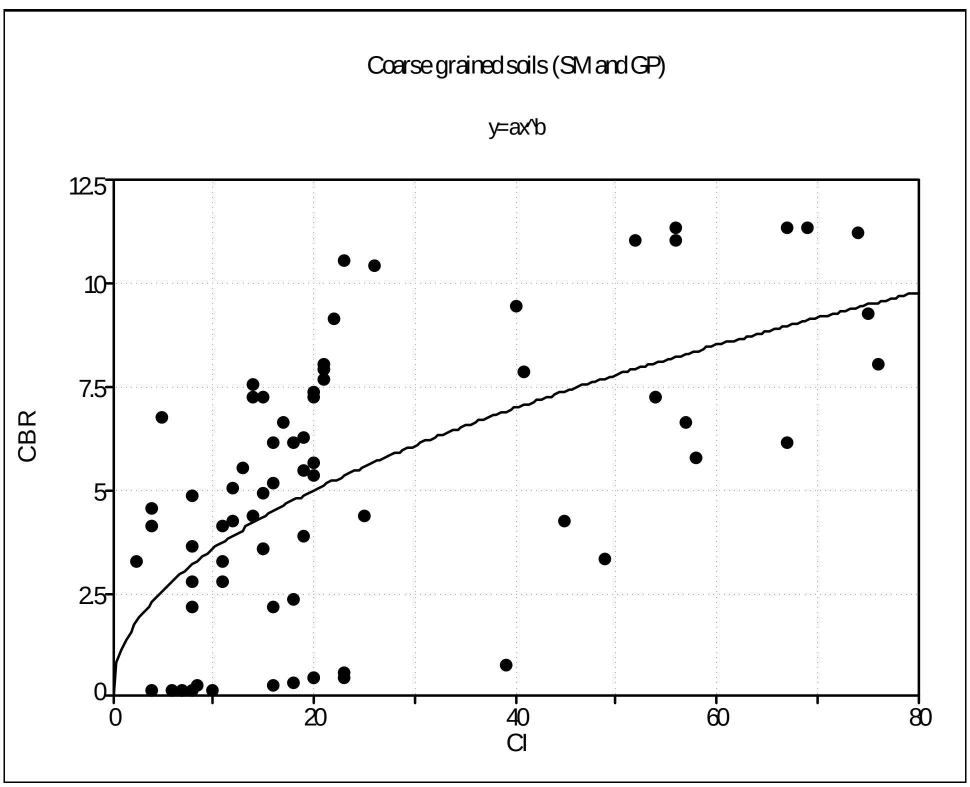


Figure 22. CBR versus CI for coarse-grained soils.

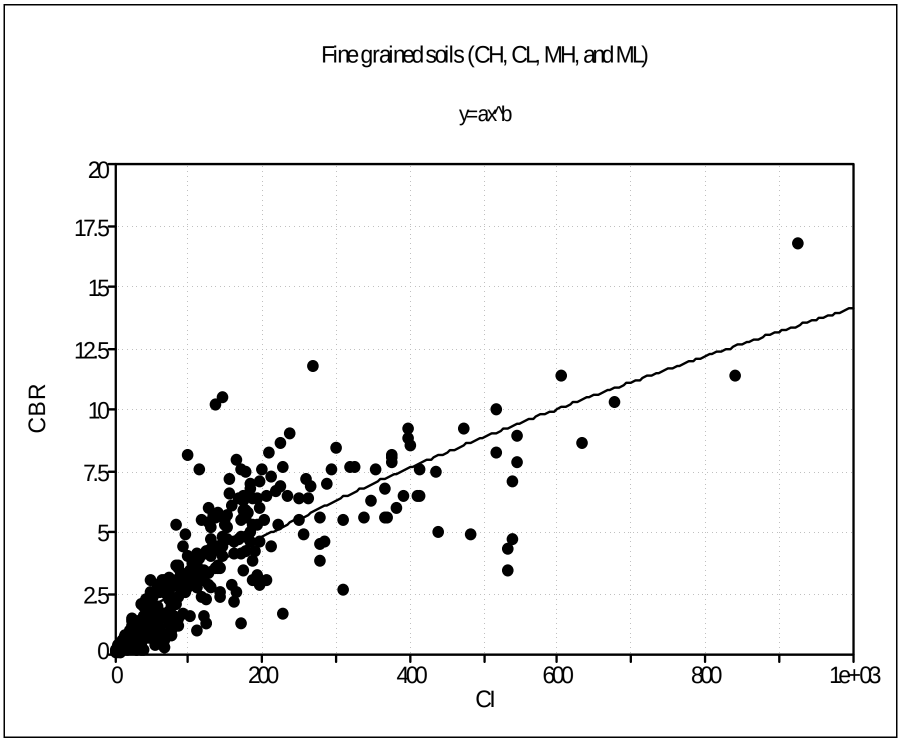


Figure 23. CBR versus CI for fine-grained soils.

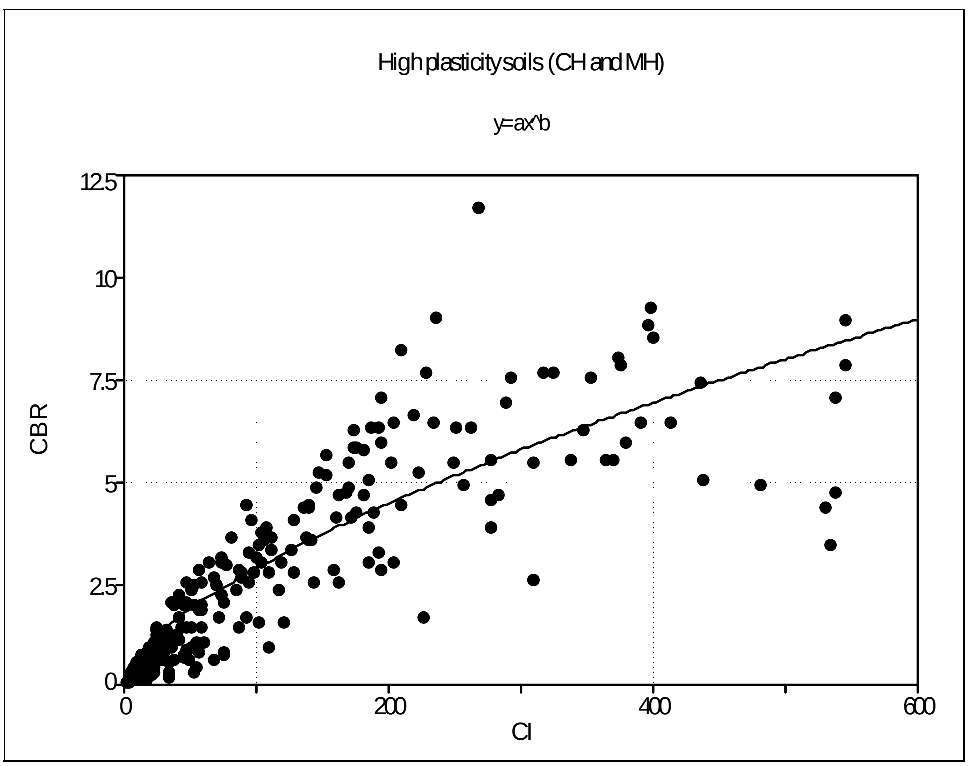


Figure 24. CBR versus CI for high-plasticity soils.

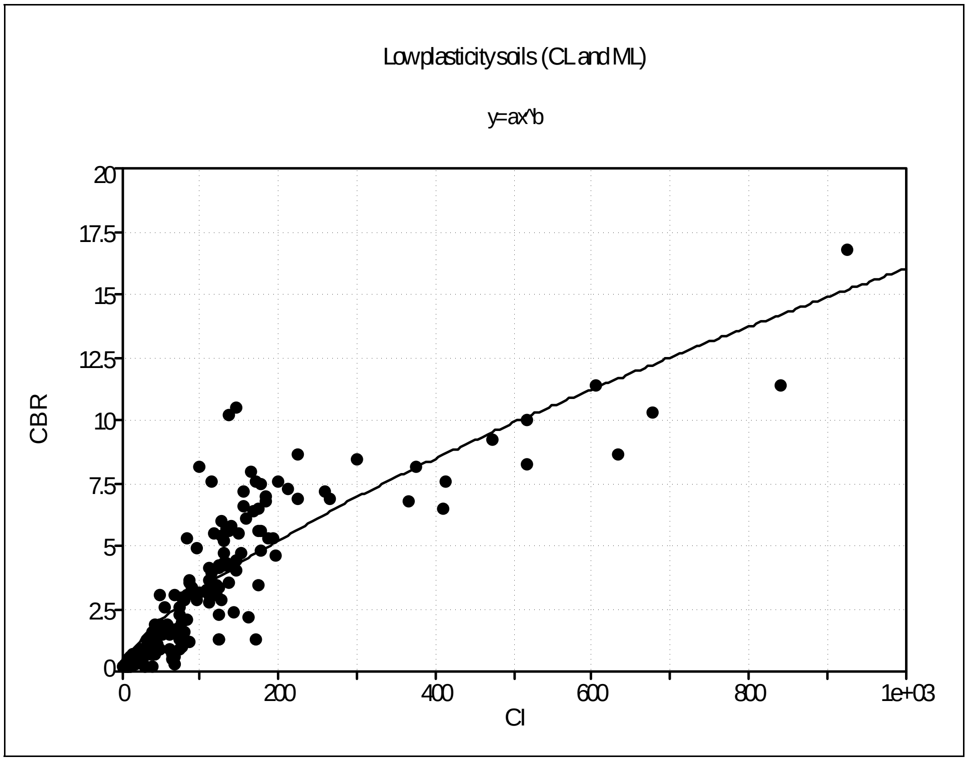


Figure 25. CBR versus CI for low-plasticity soils.

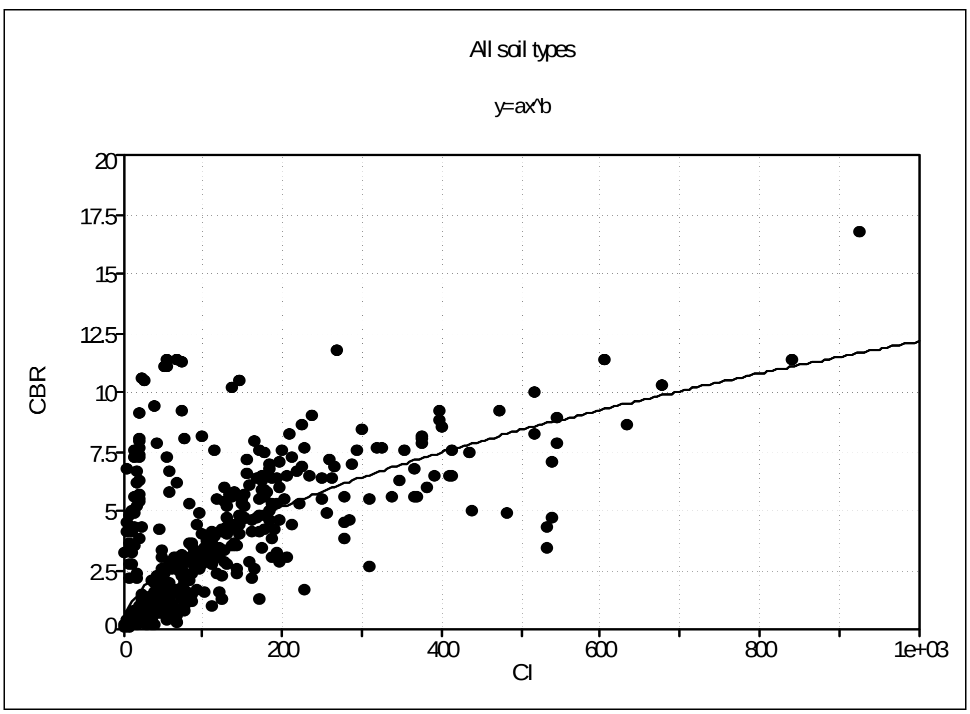


Figure 26. CBR versus CI for all CI database soils.

In addition to the individual soil types and the four subsets, regression analysis was performed on soils from each individual test site for four soil types: CH, CL, MH, and ML. Figures 27–30 show the data for individual sites, grouped by soil type, used for this analysis. Tables of regression coefficients and $R^2$ values and the regression graphs for each individual site are presented in Appendix D.

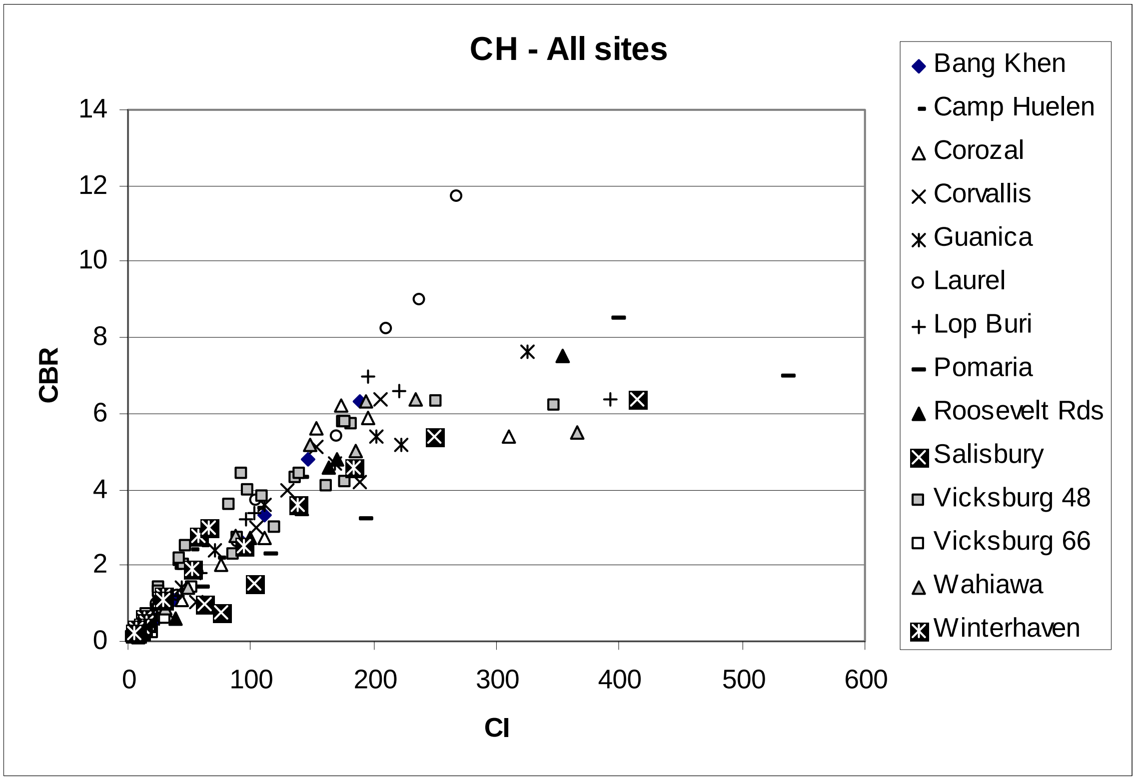


Figure 27. CBR versus CI for CH soils at individual sites.

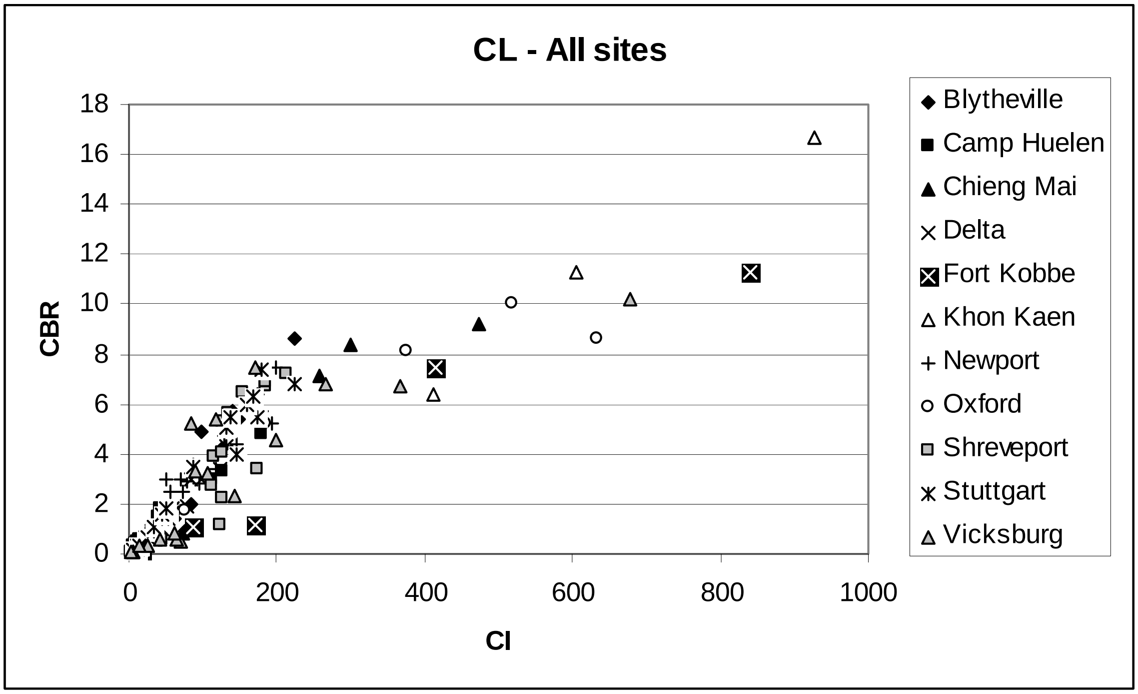


Figure 28. CBR versus CI for CL soils at individual sites.

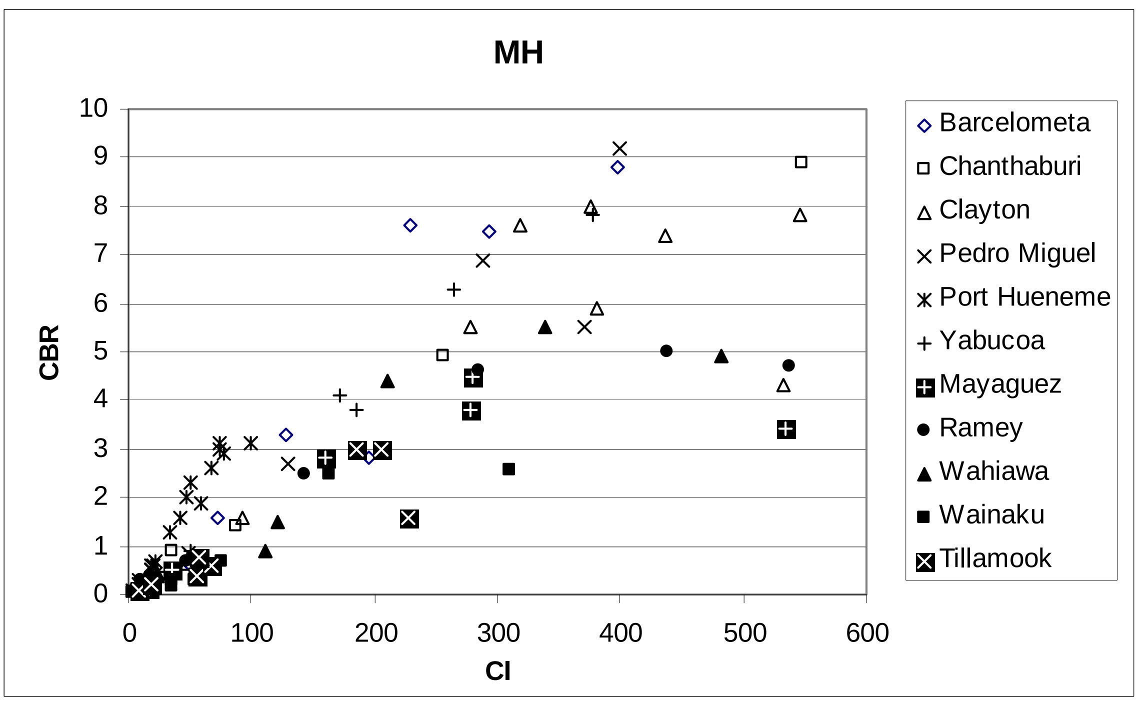


Figure 29. CBR versus CI for MH soils at individual sites.

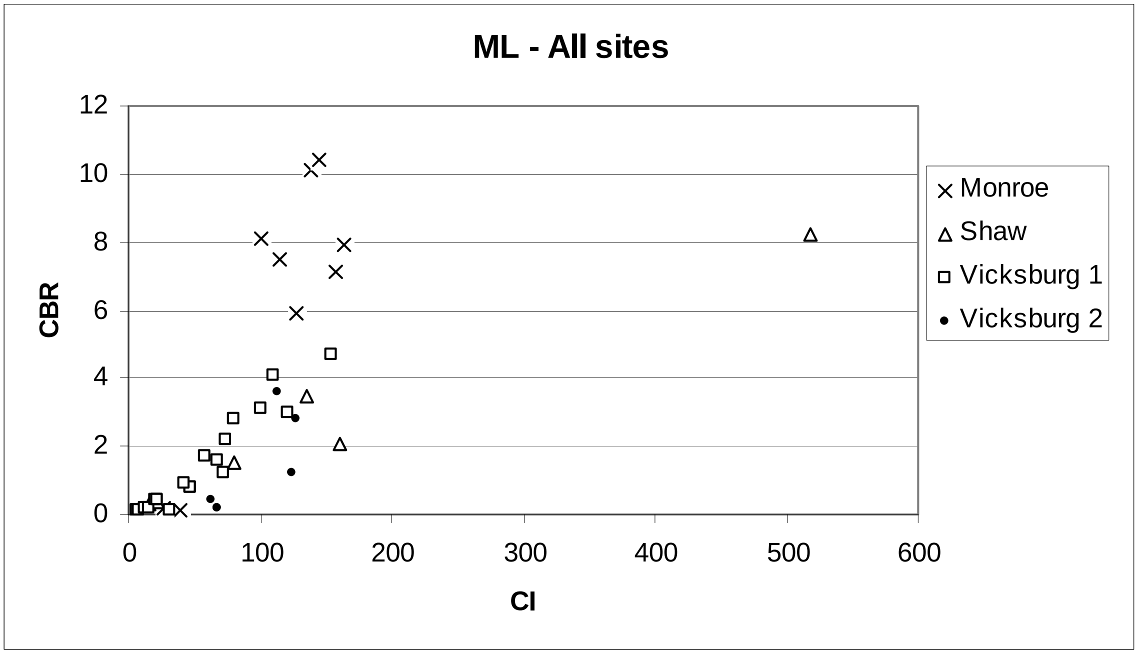


Figure 30. CBR versus CI for ML soils at individual sites.

# 5 Results

Based upon regression analysis of all CBR data from the CI database, it seems clear that an exponential equation forced through the origin provides the best fit for CBR data relative to CI, and also assures that CI and CBR will converge at zero. Higher values of $R^2$ did result when an equation of the same form was applied to site-specific data, but the corresponding curves and coefficients varied considerably. It is beyond the scope of this study to determine the properties or conditions of the individual sites that drive this variability. This is a topic for future study.

Because of poor $R^2$ values and limited data, particularly for GP, it is recommended to use the combined "Coarse-grained" soils group for SM and GP soils.

The following exponential equation represents the CBR versus CI correlations with the highest $R^2$ values that are not specific to soil from one test site:

$$CBR = aCI^b \tag{3}$$

where:

*a* and *b* are defined in Table 9.

Table 9. Coefficients and exponents of CBR prediction from CI values.

| Soil Type | USCS Classification | Coefficients and Exponents | | |
|---|---|---|---|---|
| | | *a* | *b* | $R^2$ |
| All soils | | 0.2985 | 0.5358 | 0.4715 |
| Clay, high plasticity | CH | 0.1264 | 0.6979 | 0.8516 |
| Clay, low plasticity | CL | 0.1266 | 0.6986 | 0.8701 |
| Silt, high plasticity | MH | 0.0820 | 0.7174 | 0.7715 |
| Silt, low plasticity | ML | 0.1111 | 0.7390 | 0.5193 |
| Coarse-grained | SM + GP | 1.1392 | 0.4896 | 0.3495 |
| Fine-grained | CH, CL, MH, ML | 0.1305 | 0.6776 | 0.7724 |
| High plasticity | CH + MH | 0.1460 | 0.6432 | 0.7741 |
| Low plasticity | CL + ML | 0.1281 | 0.6984 | 0.7962 |

The proposed usage of the equation is as follows:

1. For coarse-grained soils, use the "Coarse-grained" soil coefficient and exponent.

2. For fine-grained soils,

   a. Is the USCS classification known? If so, proceed using the coefficient and exponent for the appropriate USCS soil classification.

   b. If no USCS classification is available, is the soil plasticity known? If so, use the low- or high-plasticity coefficient and exponent.

   c. If no further information other than grain size is known, use the general "Fine-grained" soils coefficient and exponent.

3. If no information on the soil is known, use "All soils" coefficient and exponent.

Figure 31 shows the regression curves for the equations that result from using the coefficients given in Table 9, by soil type and soil subset.

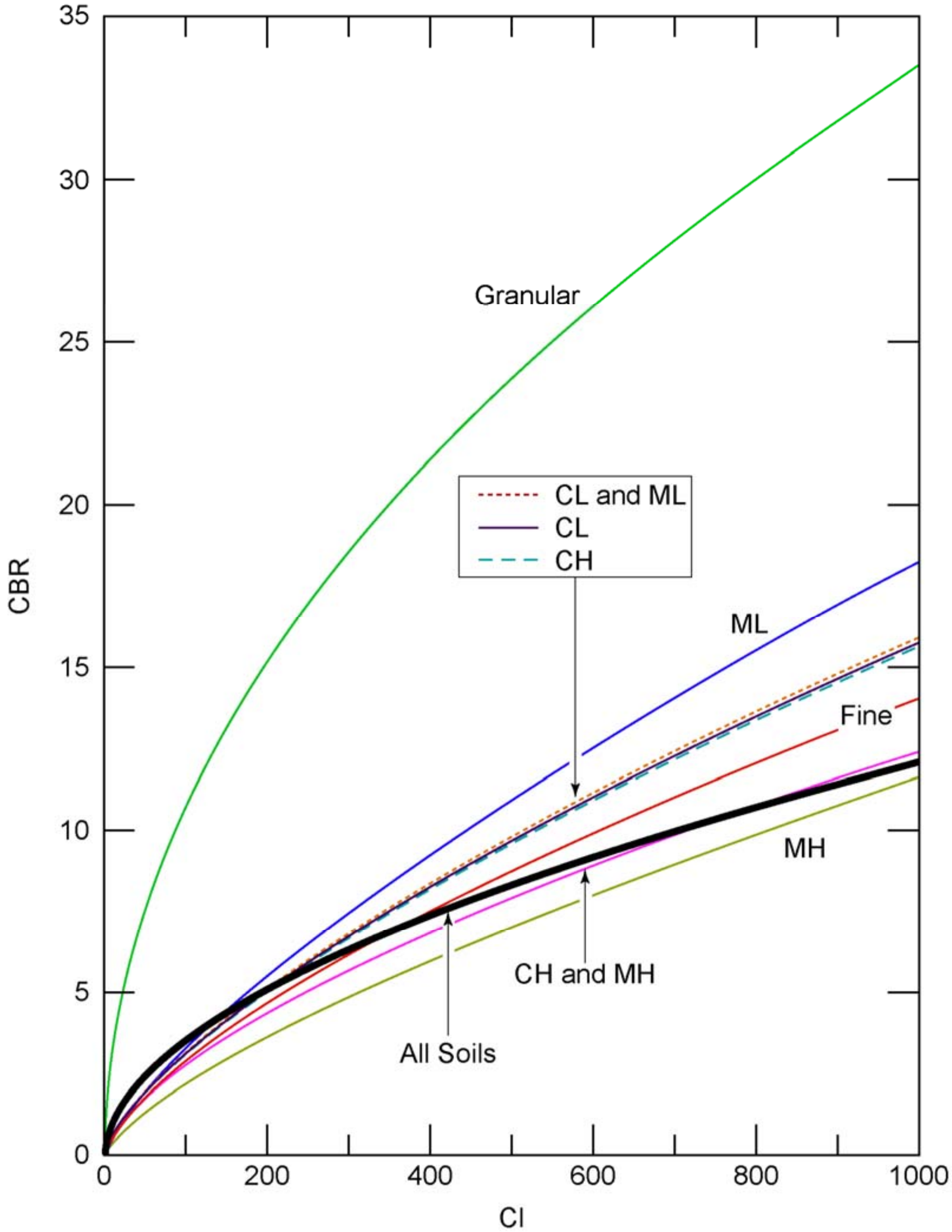


Figure 31. Correlations of CBR to CI for CI database soils.

# 6 Discussion

Regression analysis of data from the CI database indicated that an exponential equation, originating at zero, would provide predictive equations for CBR given a value of CI with reasonable $R^2$ values (0.5193−0.8701) for clay and silt soils, but not for coarse-grained soils. Because SM and GP soils had such poor $R^2$ values individually, and there was a limited amount of GP soils data available, SM and GP were combined into a soil subset to provide a final correlation equation.

The prediction yielded slightly higher (0.7962 versus 0.7741) $R^2$ values for high-plasticity versus low-plasticity clay soils. These predictions are an improvement over the $R^2$ value obtained from a regression for all soils data (regardless of soil type). For all soils data, an $R^2$ of 0.4715 is returned.

Predictions for CBR using CI correlations produced higher $R^2$ values for fine-grained soils than for course-grained soils, indicating that the equations developed are more accurate for clays and silts. This is an artifact of both the CBR and the CI tests. The field CBR test, with its blunt tip piston, is more reliable and consistent in fine-grained soils. In coarse-grained soils, where larger particles, greater than ¾ in., may restrict the piston, CBR values tend to be inconsistent and high. The trafficability cone penetrometer is known to work better in soils with some cohesion, thus it is not surprising that the correlations for coarse-grained soils are marginal at best.

Several of the equations that resulted from regression of single test location soils resulted in higher $R^2$ values than found in the USCS-based equations shown in Table 9. Although the purpose of the research is to develop generic equations based on universal soil types for global application, the site-specific information should be helpful in understanding the specific soil properties that influence soil strength and is a topic for future research.

It is important to consider the error within the CBR and CI measurements themselves when using prediction methods to determine an applicable CBR value. Any value derived from predicting CBR by a model based on actual CBR data cannot be more precise than actual measured CBR values. Freeman and Grogan (1997) indicate that the coefficient of variation for CBR of natural soils is approximately 25 percent, and therefore it is unreasonable to expect predicted values to have any higher level of accuracy. When the error in the CI reading is also factored in, CBR prediction must be used judiciously, with these limitations considered.

Selection of an alternate soil strength indicator would not necessarily overcome this problem. Tightly controlled laboratory soil strength tests (e.g., drained triaxial) have a coefficient of variation of approximately 10 percent, whereas other tests (e.g., undrained triaxial, shear vane, plate bearing subgrade modulus, deflectometer, shear box, and unconfined compressive) have coefficients of variation up to 40 percent (Freeman and Grogan 1997). Choosing a soil strength index other than CBR would not necessarily improve the accuracy of prediction models when the variability is inherent to the nature of soils and their physical and engineering properties. Furthermore, very few other strength measures benefit from the large historical database as CBR and the cone penetrometer.

In addition to the error introduced by testing methods, soils are extremely variable materials naturally. They vary both vertically in the soil profile, as a result of moisture migration and soil formation processes, and they also vary laterally. For example, during testing at the OLS demonstration site at Vandenberg Air Force Base (AFB), California, CBR values ranged from 2 to more than 80 in an area of only 100 $ft^2$ (Ryerson et al. 2008; Shoop et al. 2008a).

# 7 Conclusions

The proposed method of CBR prediction from cone index (Figure 31; Eq. 4) would provide the military planner using the OLS program with a prediction of the bearing capacity of the proposed sites' soils in areas where CI is already measured or predicted for vehicle ground trafficability.

$$CBR = aCI^{b} \tag{4}$$

where:

coefficients *a* and *b* are defined in Table 9.

The CBR values that result from the prediction may vary significantly from those of the actual in-situ soil; therefore, the prediction should be used in a conservative manner when applying these values as a basis for selection or rejection of a contingency airfield site.

It is clear that many of the correlations generated in this effort fit the data very well, especially for site-specific correlations. However, there are aspects that need further analysis. Most important among them is the need to assign coefficients based on physical parameters. It seems likely that plasticity and moisture content are at least contributing factors; however, other factors may be involved. Analysis of these factors may help in refining the soil strength predictions in the future.

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# Appendix A: Soil Designations and Cross References

| Reference | Soil Designations | | | Country | USCS Soil Class. |
|---|---|---|---|---|---|
| | Figure 2 | Figure 3 | Table 4 | | |
| U.S. Army (1948) | 1 Shreveport Gravel | | Shreveport, LA (Meriwether Supply Co. Gravel Pit) | United States | GP |
| U.S. Army (1948) | 2 Shreveport Gravelly Sand | | Shreveport, LA (Gifford Hill Sand & Gravel) | United States | GP |
| U.S. Army (1948) | 3 Fort Pierce Sand | | Fort Pierce, FL | United States | SM |
| U.S. Army (1948) | 4 Monroe Silt | | Monroe, LA | United States | ML |
| U.S. Army (1948) | 5 Fort Pierce Silty Sand | | Fort Pierce, FL | United States | SM |
| U.S. Army (1948) | 6 Vicksburg Loess | | Vicksburg, MS (WES) | United States | ML |
| U.S. Army (1948) | 7 Vicksburg Clayey Silt (WR-7) | | Delta, LA | United States | ML |
| U.S. Army (1948) | 8 Shreveport Clayey Sandy Silt | | Barksdale Army Airfield, Shreveport, LA | United States | CL |
| U.S. Army (1948) | 9 Blythewille Clayey Sandy Silt | | Blythville Army Airfield, AR | United States | CL |
| U.S. Army (1948) | 10 Vicksburg Clayey Silt (WR-6) | | Delta, La | United States | CL |
| U.S. Army (1948) | 11 Vicksburg Clayey Silt (WR-5) | | Vicksburg, MS (Rifle Range) | United States | CL |
| U.S. Army (1948) | 12 Stuttgart Silty Clay | | Stuttgart Army Airfield, Stuttgart, AR | United States | CL |
| U.S. Army (1948) | 13 Newport Clayey Sandy Silt | | Newport Army Airfield, Newport, AR | United States | CL |
| U.S. Army (1948) | 14 Camp Hulen Silty Sandy Clay | | Camp Huelen, Palacios, TX | United States | CL |
| U.S. Army (1948) | 15 Port Nuenene clay | | Port Hueneme, CA | United States | MH |
| U.S. Army (1948) | 16 Vicksburg Buckshot Clay | | Mound, LA | United States | CH |
| U.S. Army (1948) | 17 Camp Hulen Clay | | Camp Huelen, Palacios, TX | United States | CH |
| U.S. Army (1948) | 18 Winterhaven Clay | | Winterhaven, CA | United States | CH |
| Meyer (1966) | | CZ-1 | Fort Kobbe | Panama | CL |
| Meyer (1966) | | CZ-2 | Pedro Miguel | Panama | MH |
| Meyer (1966) | | H-1 | Wahiawa, Oahu, HI | United States | MH |
| Meyer (1966) | | H-2 | Wahiawa, Oahu, HI | United States | CH |

| Reference | Soil Designations | | | Country | USCS Soil Class. |
|---|---|---|---|---|---|
| | Figure 2 | Figure 3 | Table 4 | | |
| Meyer (1966) | | PR-1 | Mayaguez | Puerto Rico | MH |
| Meyer (1966) | | PR-2 | Yabucoa | Puerto Rico | MH |
| Meyer (1966) | | PR-3 | Roosevelt Roads Naval Station | Puerto Rico | CH |
| Meyer (1966) | | PR-4 | Barcelometa | Puerto Rico | MH |
| Meyer (1966) | | PR-5 | Ramey | Puerto Rico | MH |
| Meyer (1966) | | PR-6 | Corozal | Puerto Rico | CH |
| Meyer (1966) | | PR-7 | Guanica | Puerto Rico | CH |
| Meyer (1966) | | T-1 | Chanthaburi | Thailand | MH |
| Meyer (1966) | | T-2 | Lop Buri | Thailand | CH |
| Meyer (1966) | | T-3 | Bang Khen | Thailand | CH |
| Meyer (1966) | | T-4 | Chieng Mai | Thailand | CL |
| Meyer (1966) | | T-5 | Khon Kaen | Thailand | CL |
| Meyer (1966) | | US-1 | Corvallis, OR | United States | CH |
| Meyer (1966) | | US-2A | Shaw, OR | United States | ML |
| Meyer (1966) | | US-3 | Tillamook, OR | United States | MH |
| Meyer (1966) | | US-4 | Pomaria, SC | United States | CH |
| Meyer (1966) | | US-5A | Salisbury, NC | United States | CH |
| Meyer (1966) | | US-6 | Clayton, GA | United States | MH |
| Meyer (1966) | | US-7 | Oxford, AL | United States | CL |
| Meyer (1966) | | US-8 | Vicksburg, MS | United States | CL |
| Meyer (1966) | | US-9 | Vicksburg, MS | United States | CH |
| Meyer (1966) | | US-10 | Laurel, MS | United States | CH |
| Meyer (1966) | | US-11 | Vicksburg, MS | United States | CH |
| Willoughby et al. (1981) | | | Jackass Flats Test Site, NV | United States | GW |

# Appendix B: Database Field Descriptions

| | |
|---|---|
| **N = numerical feature** | **C = categorical feature** |
| **O = ordinal feature** | **B = binary feature** |

**OLS Data Point #** {N}

Specific ID number given to each line of data as a unique identifier in the database.

**JRAC Soil #** {N}

Specific ID number given to each unique soil that was identified in the Joint Rapid Airfield Construction program's ERDC database.

**Test or Sample Date** {N}

Date on which measurements or tests were performed.

**Report #** {C}

**Report Date** {N}

**Report Title** {C}

Citation information for source of soil test data.

**Country Code (ISO-3166)** {C}

Standard two-letter ID code for country in which test site is located (International Standards Organization 2005).

**Location** {C}

Geographic location of test site (name of military base, town/state, airfield name, etc.).

**Test Station** {C}

Location or ID for test site within the geographic location given above (test pit #, location #, station on runway/taxiway, etc.).

**Latitude**

Latitude given in degrees (N), minutes, and seconds as reported.

**Longitude**

Longitude given in degrees (W or E), minutes, and seconds as reported.

**Landform** {C}

The category of landform based on slope, relief, and relation to surrounding lands for the general area surrounding the test site. Hierarchical categories based on van Engelen and Wen (1995) include

*L* *Level Land*

- *LP* *Plains*
- *LL* *Plateaus*
- *LD* *Depressions*
- *LF* *Low-gradient footslopes*
- *LV* *Valley floors*

*S* *Sloping Land*

- *SM* *Medium-gradient mountains*
- *SH* *Medium-gradient hills*
- *SE* *Medium-gradient escarpment zone*
- *SR* *Ridges*
- *SU* *Mountainous highland*
- *SP* *Dissected plains*

*T* *Steep Land*

- *TM* *High-gradient mountains*
- *TH* *High-gradient hills*
- *TE* *High-gradient escarpment zone*
- *TV* *High-gradient valleys*

*C* *Lands with Composite Landforms*

- *CV* *Valleys*

*CL* *Narrow plateaus*

*CD* *Major depressions*

**Lithology of Parent Material** {C}

Category of rock type that forms the basis for the soil, primarily based on geology and mineralogy. Hierarchical categories based on van Engelen and Wen (1995) include

*I* *Igneous Rock*

*IA* *Acid igneous*

*IA1* *Granite*

*IA2* *Grano-Diorite*

*IA3* *Quartz-Diorite*

*IA4* *Rhyolite*

*II* *Intermediate igneous*

*II1* *Andesite, Trachyte, Phonolite*

*II2* *Diorite-Syenite*

*IB* *Basic igneous*

*IB1* *Gabbro*

*IB2* *Basalt*

*IB3* *Dolerite*

*IU* *Ultrabasic igneous*

*IU1* *Peridotite*

*IU2* *Pyroxenite*

*IU3* *Ilmenite, Magnetite, Ironstone, Serpentine*

*M* *Metamorphic rock*

*MA* *Acid metamorphic*

*MA1* *Quartzite*

*MA2* *Gneiss, Migmatite*

*MA3 Slate, Phyllite (peltic rocks)*

*MA4 Schist*

*MB Basic metamorphic*

*MB1 Slate, Phyllite (peltic rocks)*

*MB2 Schist*

*MB3 Gneiss rich in ferro-magnesian minerals*

*MB4 Metamorphic limestone (marble)*

*S Sedimentary rock*

*SC Classic sediments*

*SC1 Conglomerate, Breccia*

*SC2 Sandstone, Greywacke, Arkose*

*SC3 Siltstone, Mudstone, Claystone*

*SC4 Shale*

*SC5 Ironstone*

*SO Organic*

*SO1 Limestone, other carbonate rocks*

*SO2 Marl and other mixtures*

*SO3 Coals, Bitumen, and related rocks*

*SE Evaporites*

*SE1 Anhydrite, Gypsum*

*SE2 Halite*

**Deposition Type** {C}

Method of natural deposition for soil material at the test site. Categories for unconsolidated sediments based on van Engelen and Wen (1995) include

*UF Fluvial*

*UL Lacustrine*

*UM Marine*

| | |
|---|---|
| *UC* | *Colluvial* |
| *UE* | *Eolian (Aeolian)* |
| *UG* | *Glacial* |
| *UP* | *Pyroclastic* |
| *UO* | *Organic* |

**Depth to Water Table** {N}
Depth in feet to natural groundwater from grade level at test site. All values in the originating reports used feet and inches. None were converted to metric.

**Soil Type, USCS** {C}
Soil classification according to the Unified Soil Classification System. Twenty-six possible entries include

| | | |
|---|---|---|
| *1* | *GW* | *Well-graded gravel* |
| *2* | *GP* | *Poorly graded gravel* |
| *3* | *GM* | *Silty gravel* |
| *4* | *GC* | *Clayey gravel* |
| *5* | *SW* | *Well-graded sand* |
| *6* | *SP* | *Poorly graded sand* |
| *7* | *SM* | *Silty sand* |
| *8* | *SC* | *Clayey sand* |
| *9* | *ML* | *Low-compressibility silt* |
| *10* | *CL* | *Lean clay* |
| *11* | *OL* | *Organic silt or clay* |
| *12* | *MH* | *High-compressibility silt* |
| *13* | *CH* | *Fat clay* |
| *14* | *OH* | *Organic silt or clay* |
| *15* | *Pt* | *Peat* |
| *16* | *CL-ML* | *Silty clay* |
| *17* | *GW-GM* | *Well-graded gravel with silt* |

| | | |
|---|---|---|
| *18* | *GW-GC* | *Well-graded gravel with clay* |
| *19* | *GP-GM* | *Poorly graded gravel with silt* |
| *20* | *GP-GC* | *Poorly graded gravel with clay* |
| *21* | *GC-GM* | *Silty, clayey gravel* |
| *22* | *SW-SM* | *Well-graded sand with silt* |
| *23* | *SW-SC* | *Well-graded sand with clay* |
| *24* | *SP-SM* | *Poorly graded sand with silt* |
| *25* | *SP-SC* | *Poorly graded sand with clay* |
| *26* | *SC-SM* | *Silty, clayey sand* |

**Alternate Soil Type** {C}

**Alternate Soil System** {C}

Soil classification with non-USCS system.

**Soil Description** {C}

Remarks on descriptive soil characteristics included with test data (textural description, color, etc.)

**Clay Mineralogy** {C}

The dominant type of mineral in the clay fraction of the soil. Can have a large influence on mechanical behavior for certain minerals. Categories based on van Engelen and Wen (1995) include

| | |
|---|---|
| *AL* | *Allophane* |
| *CH* | *Chloritic* |
| *IL* | *Illitic* |
| *IN* | *Interstratified or Mixed* |
| *KA* | *Kaolinitic* |
| *MO* | *Montmorillonitic* |
| *SE* | *Sesquioxidic* |
| *VE* | *Vermiculitic* |

**Specific Gravity** {N}
Relative density of soil particles compared to water.

**Sample Depth Below Grade** {N}
Depth in inches from grade level at site where testing was performed.

**Plastic or Non-Plastic** {B}
Indicates whether the material passing the #40 sieve exhibits plastic behavior at some moisture content (e.g., clay) or does not (e.g., sand). During the data entry process, sources that reported numerical values for liquid limit, plastic limit, and plasticity index were entered as *P*. Sources for which the plasticity was explicitly reported as "non-plastic" were entered as *NP*. No entry in this field indicates that the source reported no liquid limit, plastic limit, or plasticity values, nor did it provide an explicit indication that the soil was non-plastic.

**LL** {N}
Liquid limit of the soil in percent. The gravimetric moisture content at an arbitrary limit between the liquid and plastic states of consistency where the soil begins to exhibit a liquid behavior and will flow under its own weight.

**PL** {N}
Plastic limit of the soil in percent. The gravimetric moisture content at an arbitrary limit between the plastic and semi-solid states of consistency where the soil begins to exhibit a plastic behavior and will deform under pressure without crumbling.

**PI** {N}
Plasticity index of the soil in percent. The numerical difference between the liquid limit and plastic limit of the soil. A larger plasticity index indicates a soil that is more likely to exhibit plastic behavior.

**Compactive Effort** {N}
The amount of energy in foot-pounds per cubic foot put into compacting a unit volume of soil in preparing a laboratory sample. Different test standards result in different compactive efforts, influencing the shape and location of the compaction curve relating soil moisture to density.

**Molding Moisture Content** {N}
The gravimetric moisture content of the soil in percent used in preparing a laboratory sample.

**Dry Density (laboratory)** {N}

The density of the soil in pounds per cubic foot used in preparing a laboratory sample. The dry density includes only the oven-dry mass of soil particles present in a unit volume, not any of the adsorbed or free water that may exist contributing to the sample's moisture content.

**Optimum Moisture Content and Maximum Density** {B}

An indication of whether the previous three measurements relate the peak on the moisture-density curve for that compaction energy (Y) or simply a single data point from a Proctor test on the moisture-density curve (N).

**Unsoaked CBR (laboratory)** {N}

**Soaked CBR (laboratory)** {N}
Laboratory measurement of the California bearing ratio in percent. The soil sample is prepared at a given compaction energy, molding moisture content, and dry density. It is then tested (unsoaked) or allowed to soak in water for four days to reach a nearly saturated moisture condition.

**Moisture Content as Tested (weight %)** {N}

**Moisture Content as Tested (volumetric %)** {N}
The moisture content of the soil tested in percent. Gravimetric moisture content is the weight of absorbed and free water in the soil that can be driven off by oven-drying divided by the dry soil weight. Volumetric moisture content is the volume of absorbed and free water relative to the total volume of soil.

**Trafficability Cone Index (CI)** {N}
Index test of soil strength used for ground vehicle mobility. Performed by pushing a standard rod with a 30° cone-shaped tip through the soil surface and recording the reaction force in pounds per square inch. The test is performed on soil that is undisturbed.

**Remolding Index** {N}

A ratio of the trafficability cone index for undisturbed soils to those that have been remolded. This gives some indication of the change in vehicle mobility after many passes have occurred.

**DCP Index (dynamic cone penetrometer)** {N}

Dynamic cone penetrometer index test for soil strength, measured in millimeters per blow. Performed by using a sliding weight, repeatedly dropped from a constant height, to dynamically drive a 60° conically tipped rod through the soil. The distance of penetration is measured versus the number of blows and can be correlated with CBR.

**Field CBR** {N}

In-situ field measurement of the California bearing ratio in percent.

**Field Dry Density** {N}

**Field Wet Density** {N}

The density of the soil measured in situ in the field in pounds per cubic foot. The dry density includes only the oven-dry mass of soil particles present in a unit volume—not any of the absorbed or free water that may exist contributing to the sample's moisture content. The wet density includes both the oven-dry mass of soil particles present in a unit volume and any of the absorbed or free water that may exist contributing to the sample's moisture content.

**¾-inch Sieve, Percent Passing** {N}

**⅜-inch Sieve, Percent Passing** {N}

**#4 Sieve, Percent Passing** {N}

**#10 Sieve, Percent Passing** {N}

**#40 Sieve, Percent Passing** {N}

**#100 Sieve, Percent Passing** {N}

**#200 Sieve, Percent Passing** {N}

**Clay, Percent** {N}

The gravimetric percentage of particles in a soil that are smaller than a certain size. Determined by shaking coarse soil particles through a stack of standard size sieves. Sand was taken as material passing through #4 sieve unless otherwise indicated. Silt was taken as material passing through #200 sieve, and clay was taken as material with grain size <0.005 mm.

**Roundness, Gravel** {N}

**Roundness, Sand** {N}

Standard measure of the relative angularity of a soil particle's edges and corners, determined visually (Krumbein and Sloss 1951).

**Sphericity, Gravel** {N}

**Sphericity, Sand** {N}

Standard measure of the aspect ratio of a soil particle's dimensions, determined visually (Krumbein and Sloss 1951).

**Remarks** {C}

Catch-all for any remarks associated with test data.

# Appendix C: Statistical Summary of CI Database

This appendix summarizes the entries in the CI Database that contain CBR data as of June 2006 based on the information gathered by the Geotechnical and Structures Laboratory (GSL), Vicksburg, MS. Sources of data and correlation analysis are from reports listed in the bibliography.

## Testing locations

There are a total of 14,574 entries in the CI database. Approximately 97 percent of the database entries come from testing locations in either the United States or Costa Rica. A small number of entries were obtained from locations in Thailand and the Panama Canal Zone. Of these, less than 4 percent (560 entries) provided useable CBR data. The statistical breakdown that follows includes only these entries.

The geographical distribution of the test sites was as follows:

United States, including Hawaii.........82.3%
Puerto Rico .........................................9.8%
Thailand ..............................................5.7%
Panama Canal Zone ............................2.3%

## Landform

Less than 40 percent of the entries (220) included a landform designation. Of these, 167 (76 percent) were noted as Level Land, with the remaining 53 (24 percent) noted as Sloping Land. No second level categories were given.

## Lithology of parent material

Figure C1 and Table C1 below show the distribution of the descriptors used for the lithology of parent material. Only 210 data entries reported this information, 37 percent of the total.

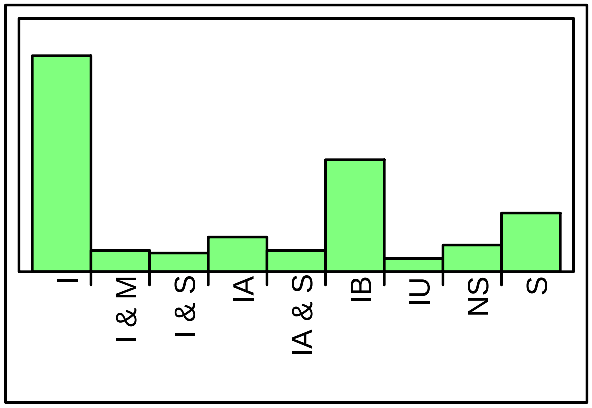



Figure C1. Lithology of parent material.

The observed lithologies were distributed into the proportions shown in Table C1. Codes are shown in Table C2 below.

Table C1. Breakdown of lithology of parent material.

| Level | Count | Probability |
|---|---|---|
| I | 85 | 0.40670 |
| I & M | 9 | 0.04306 |
| I & S | 8 | 0.03828 |
| IA | 14 | 0.06699 |
| IA & S | 9 | 0.04306 |
| IB | 44 | 0.21053 |
| IU | 6 | 0.02871 |
| NS | 11 | 0.05263 |
| S | 23 | 0.11005 |
| Total | 209 | 1.00000 |

Table C2. Lithology descriptors (from OLS database format).

| Major Class | | Group | | Type | |
|---|---|---|---|---|---|
| I | Igneous Rock | IA | Acid Igneous | IA1 | Granite |
| | | | | IA2 | Grano-Diorite |
| | | | | IA3 | Quartz-Diorite |
| | | | | IA4 | Rhyolite |
| | | II | Intermediate Igneous | II1 | Andesite, Trachyte, Phonolite |
| | | | | II2 | Diorite-Syenite |
| | | IB | Basic Igneous | IB1 | Gabbro |
| | | | | IB2 | Basalt |
| | | | | IB3 | Dolerite |
| | | IU | Ultrabasic Igneous | IU1 | Peridotite |
| | | | | IU2 | Pyroxenite |
| | | | | IU3 | Ilmenite, Magnetite, Ironstone, Serpentine |
| M | Metamorphic Rock | MA | Acid Metamorphic | MA1 | Quartzite |
| | | | | MA2 | Gneiss, Migmatite |
| | | | | MA3 | Slate, Phyllite (peltic rocks) |
| | | | | MA4 | Schist |
| | | MB | Basic Metamorphic | MB1 | Slate, Phyllite (peltic rocks) |
| | | | | MB2 | Schist |
| | | | | MB3 | Gneiss rich in ferro-magnesian minerals |
| | | | | MB4 | Metamorphic limestone (marble) |
| S | Sedimentary Rock | SC | Classic Sediments | SC1 | Conglomerate, Breccia |
| | | | | SC2 | Sandstone, Greywacke, Arkose |
| | | | | SC3 | Siltstone, Mudstone, Claystone |
| | | | | SC4 | Shale |
| | | | | SC5 | Ironstone |
| | | SO | Organic | SO1 | Limestone, other carbonate rocks |
| | | | | SO2 | Marl and other mixtures |
| | | | | SO3 | Coals, Bitumen, and related rocks |
| | | SE | Evaporites | SE1 | Anhydrite, Gypsum |
| | | | | SE2 | Halite |

## Deposition type

Only 10 of the 567 entries (1.8 percent) indicated deposition type. All were UE (Aeolian).

## Depth to water table

None of the entries noted depth to the water table.

## Soil classification

Figure C2 shows the relative abundance of the various soil types whereas Table C3 gives a numerical breakdown.

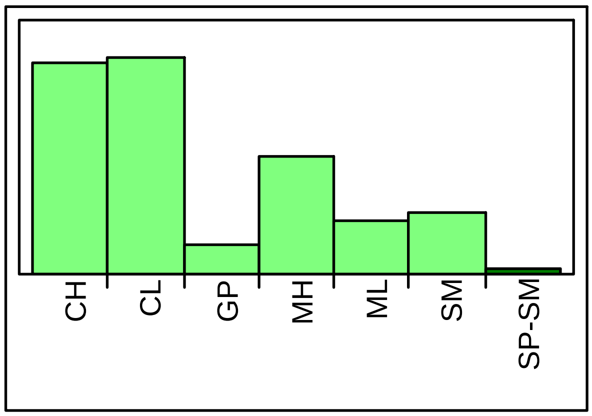



Figure C2. Distribution of soil types among CBR entries in the CI database.

Table C3. Breakdown of soil classifications within the database.

| Level | Count | Probability |
|---|---|---|
| CH | 170 | 0.30249 |
| CL | 174 | 0.30961 |
| GP | 25 | 0.04448 |
| MH | 95 | 0.16904 |
| ML | 44 | 0.07829 |
| SM | 49 | 0.08719 |
| SP-SM | 5 | 0.00890 |
| Total | 562 | 1.00000 |

## Clay mineralogy

Figure C3 and Table C4 summarize the data for clay mineralogy for the CBR entries. There were 209 entries, or 37 percent of the CBR data, containing clay mineralogy descriptions.

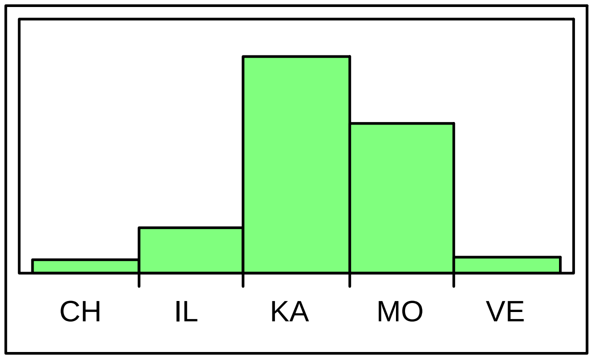



Figure C3. Distribution of entries for clay mineralogy.

Table C4. Percentage distribution of clay mineralogy.

| Level | Count | Probability |
|---|---|---|
| CH | 7 | 0.03349 |
| IL | 22 | 0.10526 |
| KA | 102 | 0.48804 |
| MO | 70 | 0.33493 |
| VE | 8 | 0.03828 |
| Total | 209 | 1.00000 |

## Physical property data and strength index test data

Of the 564 total entries, all are described as either plastic (483) or nonplastic (81). The soil types having plasticity characteristics include CH, CL, MH, ML, SM, and SP-SM.

Table C5 below lists the minimum and maximum range of values for the CI database by soil type, for the moisture content as tested (gravimetric, percent), laboratory dry density (pcf), field CBR, and Trafficability Cone Index. Remolding Index was not given for any of these entries. The percent column next to each range reflects the number of entries for that soil type used to determine those ranges.

Ranges of values for the Atterberg limits are listed for the CBR entries in the CI database in Table C6. Figures C4 through C5 graphically show the Atterberg ranges for the entries in the database.

Figures C6 through C11 show the range of values for the CI database for the dry density, moisture content, trafficability cone, remolding index, rating cone, field CBR, and field dry density.

Figures C12 through C16 show the range of values for Atterberg limits, moisture content as tested, trafficability cone, and field CBR for each major soil type in the database.

Table C5. Breakdown of significant parameters by soil type among CBR entries in the CI database.

| Soil Type | Number of Entries | Specific Gravity | Percent | Moisture Content (% as tested) | Percent | Dry Density (pcf) | Percent | Field CBR (%) | Percent | Trafficability Cone Index | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min / Max | % | Min / Max | % | Min / Max | % | Min / Max | % | Min / Max | % |
| CH | 170 | 2.50 / 2.82 | 57 | 16.6 / 90.6 | 100 | 47 / 102 | 57 | 0.09 / 11.7 | 100 | 4 / 538 | 100 |
| CL | 174 | 2.64 / 2.71 | 17 | 8.3 / 46.5 | 100 | 81.3 / 118.1 | 17 | 0.1 / 16.7 | 100 | 2 / 926 | 100 |
| GP | 25 | – | 0 | 0.3 / 10.2 | 100 | – | 0 | 0.1 / 11.3 | 100 | 7 / 76 | 100 |
| MH | 95 | 2.42 / 3.1 | 80 | 25.1 / 92.2 | 100 | 47.9 / 87.8 | 80 | 0.04 / 9.2 | 100 | 3 / 547 | 100 |
| ML | 44 | 2.79 / 2.79 | 14 | 14.2 / 35.8 | 100 | 83.1 / 94 | 14 | 0.1 / 10.4 | 100 | 7 / 581 | 100 |
| SM | 49 | – | 0 | 0 / 7.5 | 100 | 100.5 / 114 | 8 | .1 | 100 | 2.5 / 49 | 92 |
| SP-SM | 5 | – | 0 | 1.2 / 2.3 | 80 | 96 / 129.2 | 80 | 4 / 25 | 80 | – | 0 |
| Total entries | 562 | | | | | | | | | | |

Table C6. Ranges for Atterberg limits for all soil types among CBR entries in the CI database.

| Soil Type | Number of Entries | Percent of Total | Liquid Limit | | Plastic Limit | | Plastic Index | |
|---|---|---|---|---|---|---|---|---|
| | | | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum |
| CH | 170 | 100 | 50 | 130 | 19 | 48 | 22 | 82 |
| CL | 174 | 100 | 23 | 45 | 15 | 25 | 8 | 27 |
| GP | 25 | 0 | – | – | – | – | – | – |
| MH | 95 | 100 | 53 | 96 | 28 | 77 | 11 | 38 |
| ML | 44 | 77 | 26 | 45 | 23 | 27 | 2 | 18 |
| SM | 49 | 18 | 23 | 23 | 21 | 21 | 2 | 2 |
| SP-SM | 5 | 0 | – | – | – | – | – | – |
| Total entries | 562 | | | | | | | |

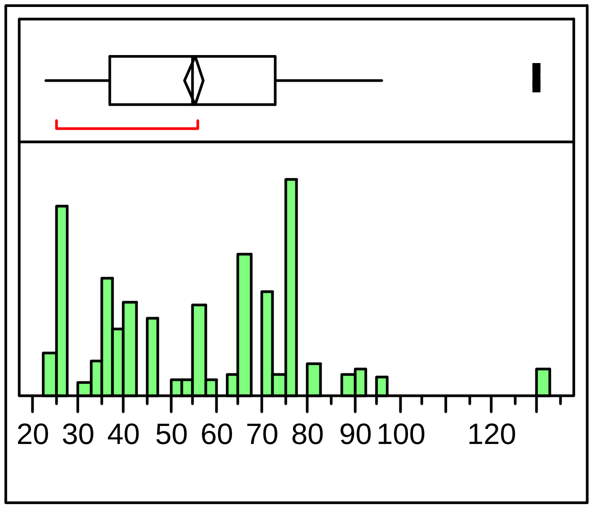



Figure C4. Range of liquid limits for CBR entries in the CI database.

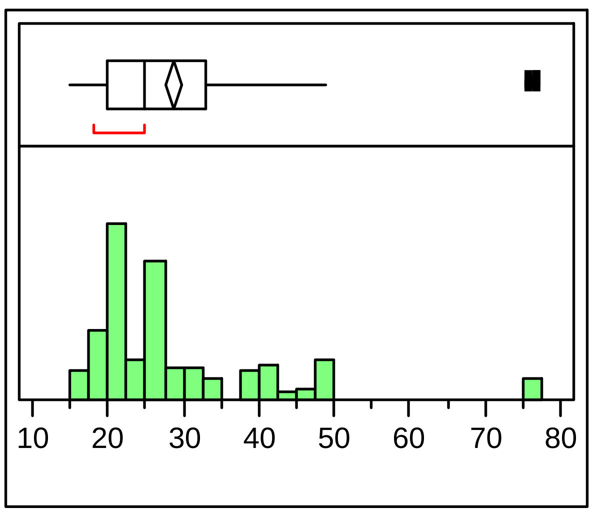



Figure C5. Range of plastic limits for CBR entries in the CI database.

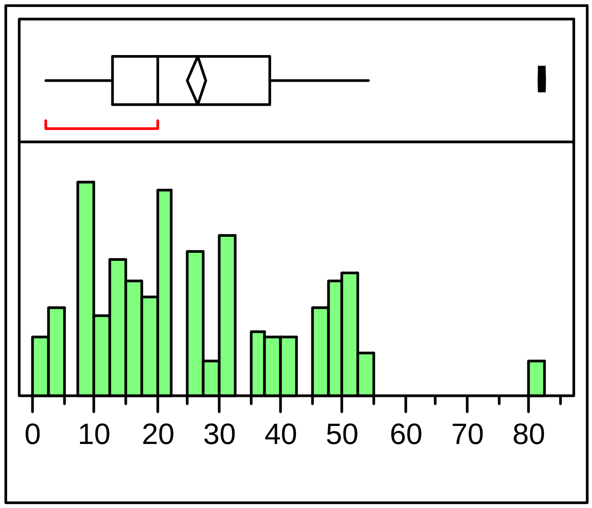



Figure C6. Range of plastic index for CI database.

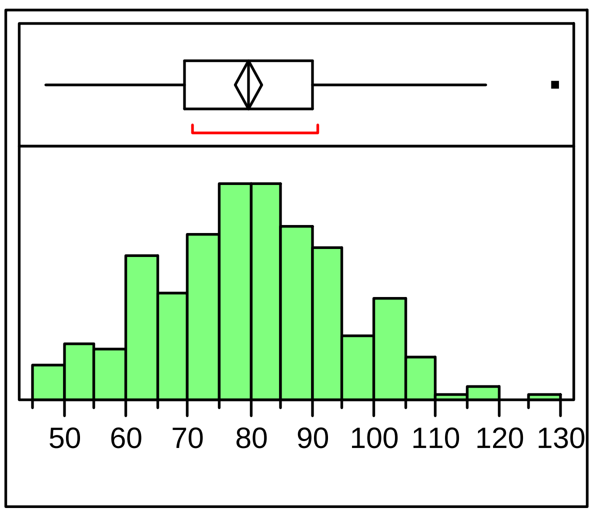



Figure C7. Range of dry density values (pcf) for CBR entries for the CI database.

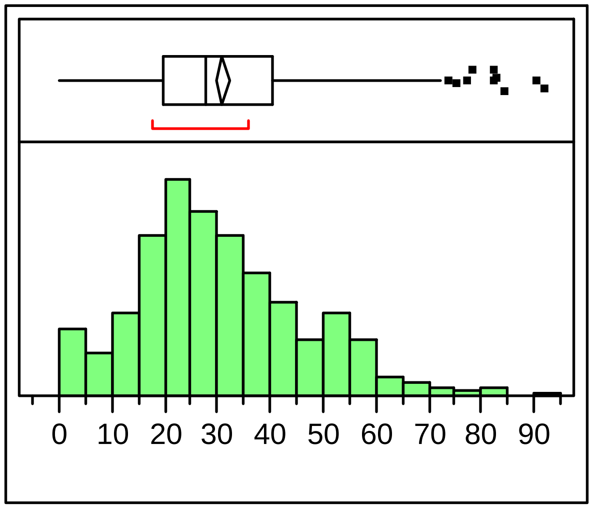
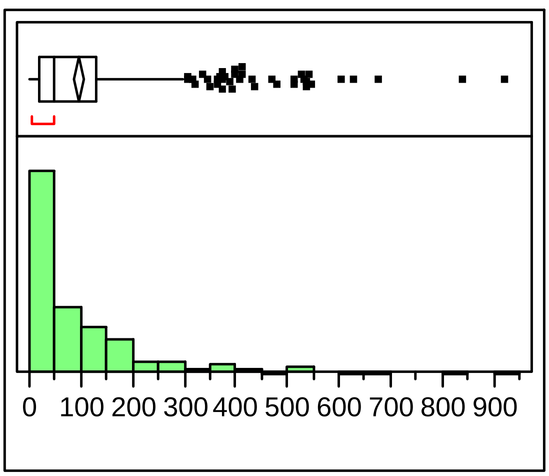
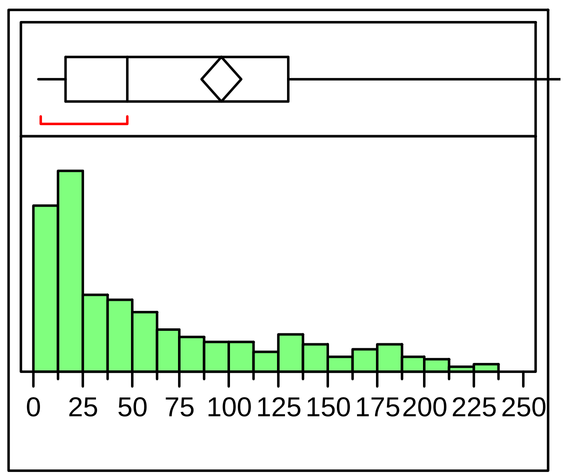



Figure C8. Range of moisture content as tested values for CI database.




a.




b.

Figure C9. Range of trafficability cone index values for CI database. (a) Shows all CI data. (b) Shows all data below 250 after the 51 CI readings greater than 250 (10 percent of the population) were removed.

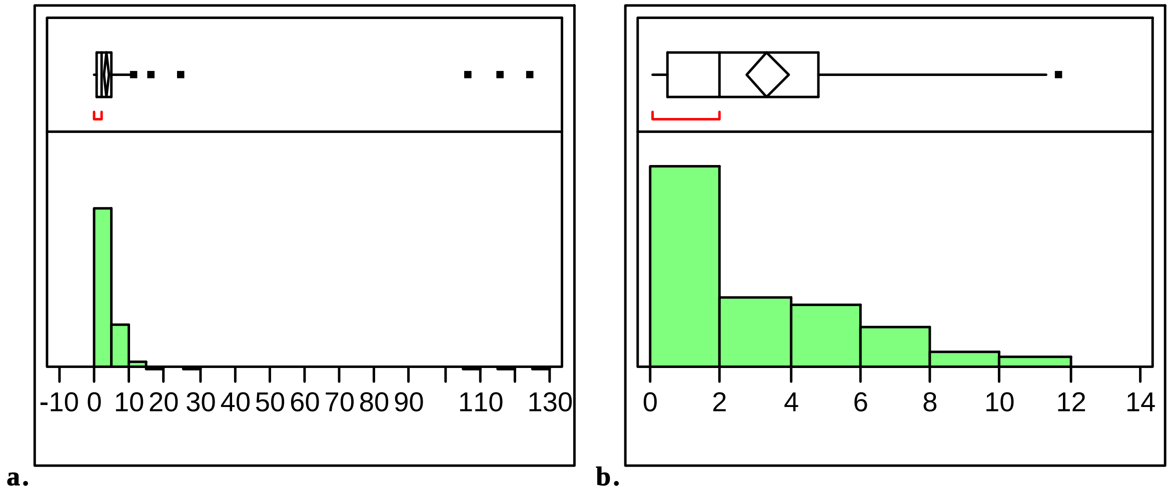



Figure C10. Range of field CBR values for CI database. (a) Shows all data. (b) Shows only data below 14, excluding five data points out of 563.

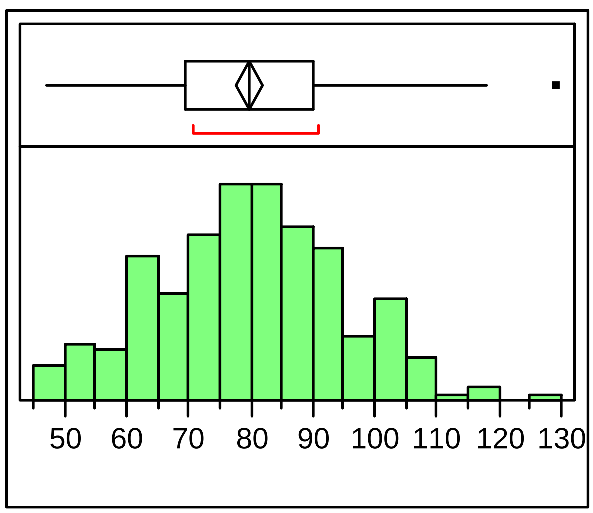
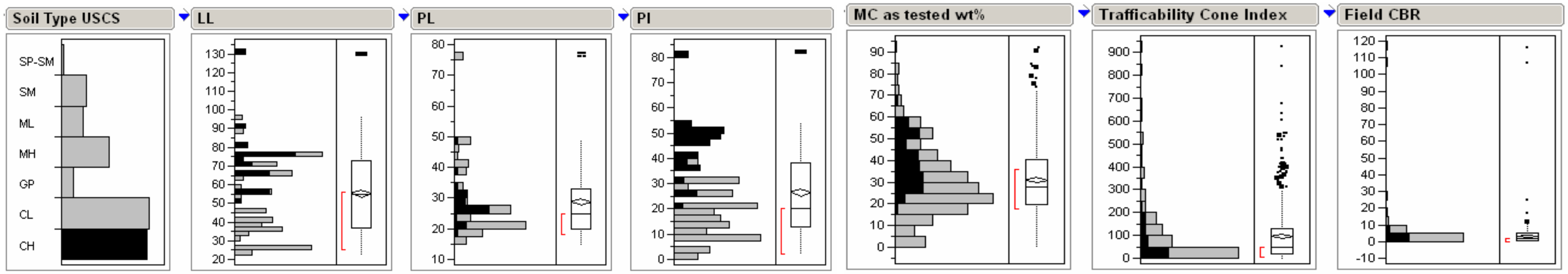



Figure C11. Range of lab dry density (pcf) values for CBR entries in the CI database.




**Frequencies**

| Level | Count | Prob |
|---|---|---|
| CH | 170 | 0.30249 |
| CL | 174 | 0.30961 |
| GP | 25 | 0.04448 |
| MH | 95 | 0.16904 |
| ML | 44 | 0.07829 |
| SM | 49 | 0.08719 |
| SP-SM | 5 | 0.00890 |
| Total | 562 | 1.00000 |
| N Missing | 1 | |
| 7 Levels | | |

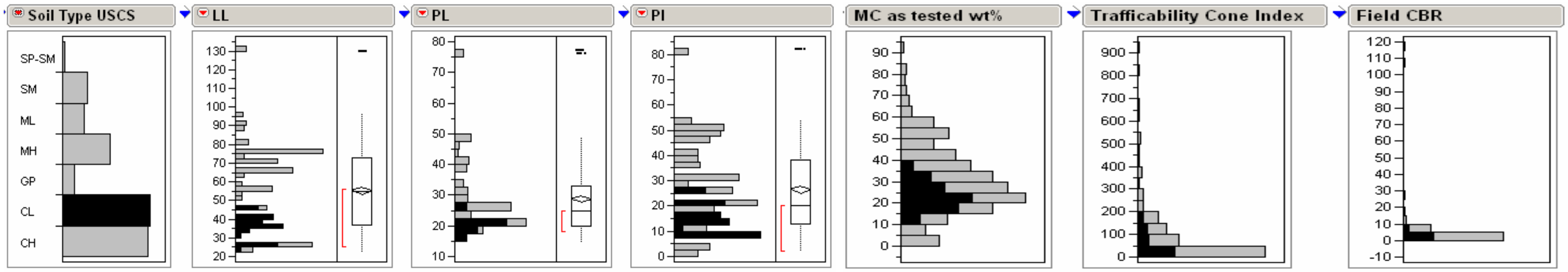
**Quantiles**

| | | LL | PL | PI | MC as tested wt% | Trafficability Cone Index | Field CBR |
|---|---|---|---|---|---|---|---|
| 100.0% | maximum | 130.00 | 77.000 | 82.000 | 92.200 | 926.00 | 116.00 |
| 99.5% | | 130.00 | 77.000 | 82.000 | 85.740 | 715.26 | 40.17 |
| 97.5% | | 96.00 | 76.000 | 54.000 | 67.760 | 487.25 | 10.49 |
| 90.0% | | 77.00 | 46.000 | 51.000 | 54.200 | 228.60 | 7.47 |
| 75.0% | quartile | 73.00 | 33.000 | 38.000 | 40.700 | 130.00 | 4.82 |
| 50.0% | median | 55.00 | 25.000 | 20.000 | 28.000 | 48.00 | 1.95 |
| 25.0% | quartile | 37.00 | 20.000 | 13.000 | 19.700 | 17.00 | 0.50 |
| 10.0% | | 26.00 | 19.000 | 8.000 | 12.620 | 8.16 | 0.20 |
| 2.5% | | 23.00 | 17.000 | 2.000 | 2.205 | 4.00 | 0.10 |
| 0.5% | | 23.00 | 15.000 | 2.000 | 0.000 | 2.88 | 0.0763 |
| 0.0% | minimum | 23.00 | 15.000 | 2.000 | 0.000 | 2.00 | 0.04 |

**Moments**

| | LL | PL | PI | MC as tested wt% | Trafficability Cone Index | Field CBR |
|---|---|---|---|---|---|---|
| Mean | 55.259336 | 28.746888 | 26.512448 | 30.994296 | 95.790778 | 3.3552313 |
| Std Dev | 22.685529 | 12.331114 | 17.107853 | 16.55371 | 124.42931 | 7.1482702 |
| Std Err Mean | 1.0332975 | 0.5616669 | 0.7792414 | 0.6988982 | 5.2912726 | 0.3015316 |
| upper 95% Mean | 57.289671 | 29.850512 | 28.043586 | 32.367078 | 106.18427 | 3.9475001 |
| lower 95% Mean | 53.229001 | 27.643264 | 24.98131 | 29.621514 | 85.397285 | 2.7629625 |
| N | 482 | 482 | 482 | 561 | 553 | 562 |

Figure C12. CH soil type: range of values for Atterberg limits, moisture content, trafficability cone index, and field CBR.




Frequencies

| Level | Count | Prob |
|---|---|---|
| CH | 170 | 0.30249 |
| CL | 174 | 0.30961 |
| GP | 25 | 0.04448 |
| MH | 95 | 0.16904 |
| ML | 44 | 0.07829 |
| SM | 49 | 0.08719 |
| SP-SM | 5 | 0.00890 |
| Total | 562 | 1.00000 |
| N Missing | 1 | |
| 7 Levels | | |

Quantiles

| | | LL | PL | PI | MC as tested wt% | Trafficability Cone Index | Field CBR |
|---|---|---|---|---|---|---|---|
| 100.0% | maximum | 130.00 | 77.000 | 82.000 | 92.200 | 926.00 | 116.00 |
| 99.5% | | 130.00 | 77.000 | 82.000 | 85.740 | 715.26 | 40.17 |
| 97.5% | | 96.00 | 76.000 | 54.000 | 67.760 | 487.25 | 10.49 |
| 90.0% | | 77.00 | 46.000 | 51.000 | 54.200 | 228.60 | 7.47 |
| 75.0% | quartile | 73.00 | 33.000 | 38.000 | 40.700 | 130.00 | 4.82 |
| 50.0% | median | 55.00 | 25.000 | 20.000 | 28.000 | 48.00 | 1.95 |
| 25.0% | quartile | 37.00 | 20.000 | 13.000 | 19.700 | 17.00 | 0.50 |
| 10.0% | | 26.00 | 19.000 | 8.000 | 12.620 | 8.16 | 0.20 |
| 2.5% | | 23.00 | 17.000 | 2.000 | 2.205 | 4.00 | 0.10 |
| 0.5% | | 23.00 | 15.000 | 2.000 | 0.000 | 2.88 | 0.0763 |
| 0.0% | minimum | 23.00 | 15.000 | 2.000 | 0.000 | 2.00 | 0.04 |

Moments

| | LL | PL | PI | MC as tested wt% | Trafficability Cone Index | Field CBR |
|---|---|---|---|---|---|---|
| Mean | 55.259336 | 28.746888 | 26.512448 | 30.994296 | 95.790778 | 3.3552313 |
| Std Dev | 22.685529 | 12.331114 | 17.107853 | 16.55371 | 124.42931 | 7.1482702 |
| Std Err Mean | 1.0332975 | 0.5616669 | 0.7792414 | 0.6988982 | 5.2912726 | 0.3015316 |
| upper 95% Mean | 57.289671 | 29.850512 | 28.043586 | 32.367078 | 106.18427 | 3.9475001 |
| lower 95% Mean | 53.229001 | 27.643264 | 24.98131 | 29.621514 | 85.397285 | 2.7629625 |
| N | 482 | 482 | 482 | 561 | 553 | 562 |

Figure C13. CL soil type: range of values for Atterberg limits, moisture content, trafficability cone index, and field CBR.

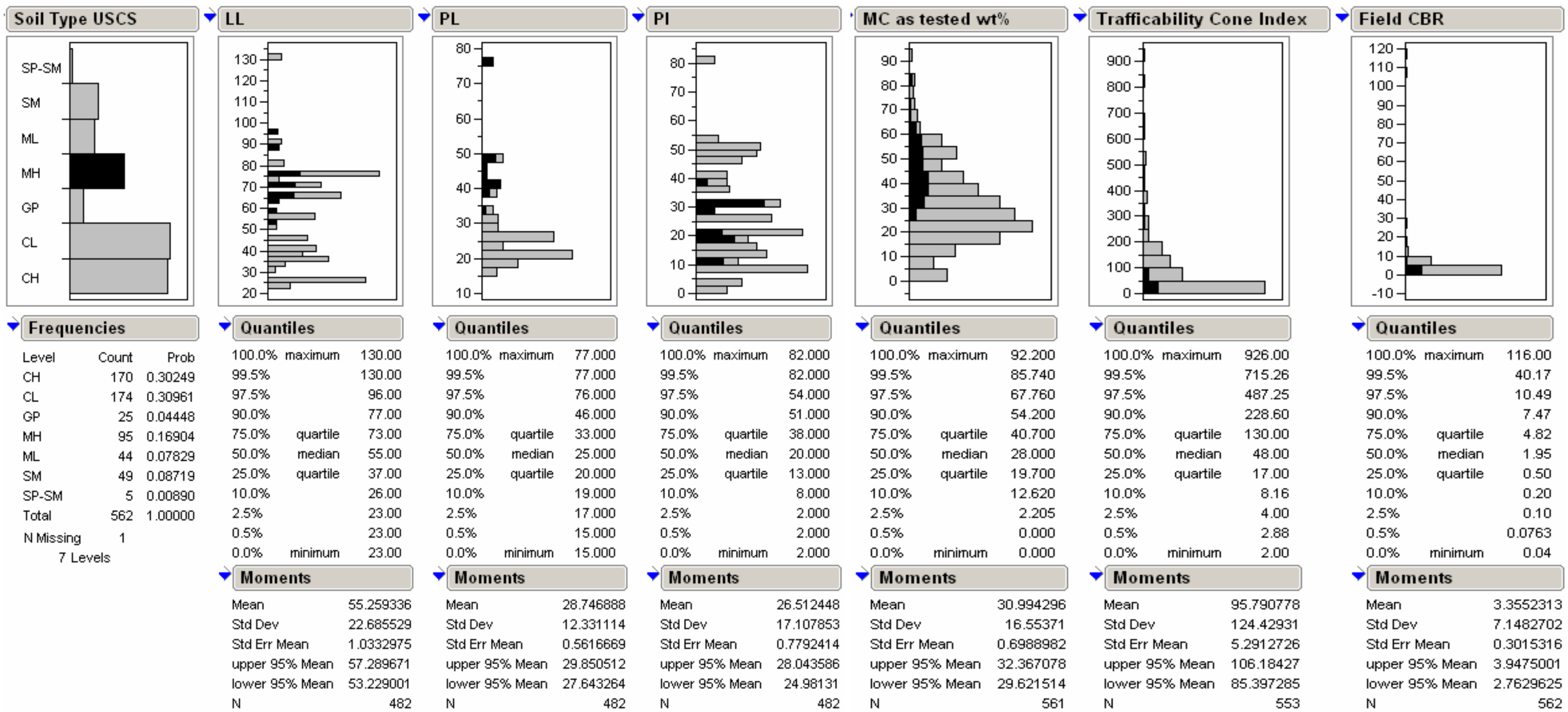
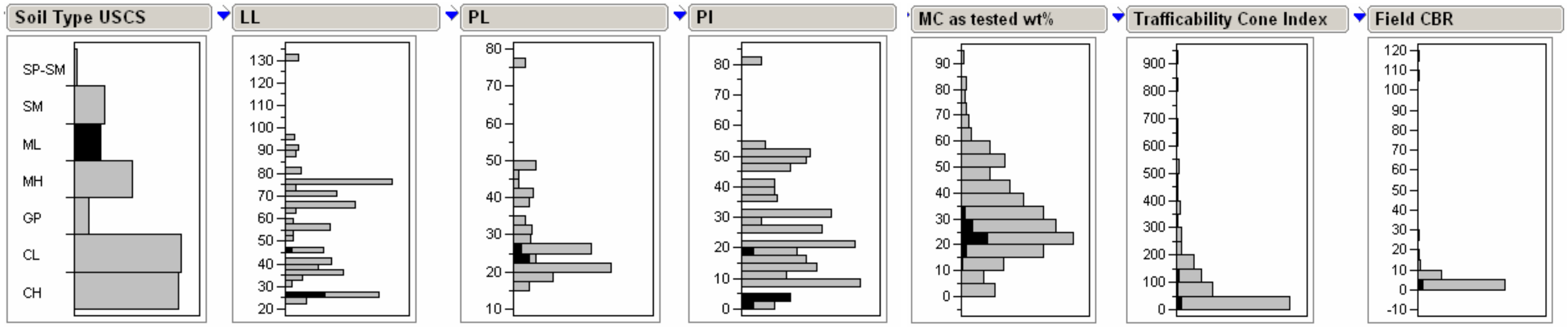



Figure C14. MH soil type: range of values for Atterberg limits, moisture content, trafficability cone index, and field CBR.




**Frequencies**

| Level | Count | Prob |
|---|---|---|
| CH | 170 | 0.30249 |
| CL | 174 | 0.30961 |
| GP | 25 | 0.04448 |
| MH | 95 | 0.16904 |
| ML | 44 | 0.07829 |
| SM | 49 | 0.08719 |
| SP-SM | 5 | 0.00890 |
| Total | 562 | 1.00000 |
| N Missing | 1 | |
| 7 Levels | | |

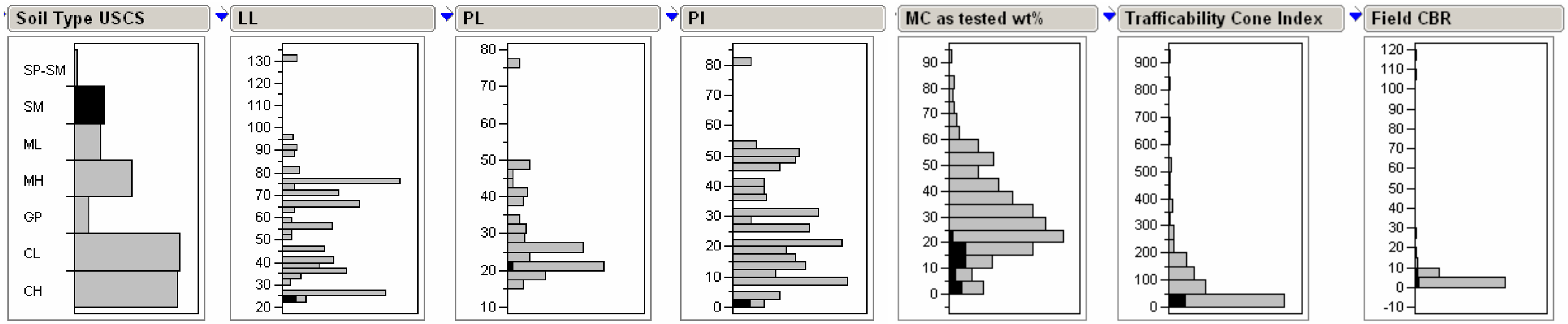
**Quantiles**

| | | LL | PL | PI | MC as tested wt% | Trafficability Cone Index | Field CBR |
|---|---|---|---|---|---|---|---|
| 100.0% | maximum | 130.00 | 77.000 | 82.000 | 92.200 | 926.00 | 116.00 |
| 99.5% | | 130.00 | 77.000 | 82.000 | 85.740 | 715.26 | 40.17 |
| 97.5% | | 96.00 | 76.000 | 54.000 | 67.760 | 487.25 | 10.49 |
| 90.0% | | 77.00 | 46.000 | 51.000 | 54.200 | 228.60 | 7.47 |
| 75.0% | quartile | 73.00 | 33.000 | 38.000 | 40.700 | 130.00 | 4.82 |
| 50.0% | median | 55.00 | 25.000 | 20.000 | 28.000 | 48.00 | 1.95 |
| 25.0% | quartile | 37.00 | 20.000 | 13.000 | 19.700 | 17.00 | 0.50 |
| 10.0% | | 26.00 | 19.000 | 8.000 | 12.620 | 8.16 | 0.20 |
| 2.5% | | 23.00 | 17.000 | 2.000 | 2.205 | 4.00 | 0.10 |
| 0.5% | | 23.00 | 15.000 | 2.000 | 0.000 | 2.88 | 0.0763 |
| 0.0% | minimum | 23.00 | 15.000 | 2.000 | 0.000 | 2.00 | 0.04 |

**Moments**

| | LL | PL | PI | MC as tested wt% | Trafficability Cone Index | Field CBR |
|---|---|---|---|---|---|---|
| Mean | 55.259336 | 28.746888 | 26.512448 | 30.994296 | 95.790778 | 3.3552313 |
| Std Dev | 22.685529 | 12.331114 | 17.107853 | 16.55371 | 124.42931 | 7.1482702 |
| Std Err Mean | 1.0332975 | 0.5616669 | 0.7792414 | 0.6988982 | 5.2912726 | 0.3015316 |
| upper 95% Mean | 57.289671 | 29.850512 | 28.043586 | 32.367078 | 106.18427 | 3.9475001 |
| lower 95% Mean | 53.229001 | 27.643264 | 24.98131 | 29.621514 | 85.397285 | 2.7629625 |
| N | 482 | 482 | 482 | 561 | 553 | 562 |

Figure C15. ML soil type: range of values for Atterberg limits, moisture content, trafficability cone index, and field CBR.




**Frequencies** (Soil Type USCS)

| Level | Count | Prob |
|---|---|---|
| CH | 170 | 0.30249 |
| CL | 174 | 0.30961 |
| GP | 25 | 0.04448 |
| MH | 95 | 0.16904 |
| ML | 44 | 0.07829 |
| SM | 49 | 0.08719 |
| SP-SM | 5 | 0.00890 |
| Total | 562 | 1.00000 |
| N Missing | 1 | |
| 7 Levels | | |

**Quantiles**

| Quantile | | LL | PL | PI | MC as tested wt% | Trafficability Cone Index | Field CBR |
|---|---|---|---|---|---|---|---|
| 100.0% | maximum | 130.00 | 77.000 | 82.000 | 92.200 | 926.00 | 116.00 |
| 99.5% | | 130.00 | 77.000 | 82.000 | 85.740 | 715.26 | 40.17 |
| 97.5% | | 96.00 | 76.000 | 54.000 | 67.760 | 487.25 | 10.49 |
| 90.0% | | 77.00 | 46.000 | 51.000 | 54.200 | 228.60 | 7.47 |
| 75.0% | quartile | 73.00 | 33.000 | 38.000 | 40.700 | 130.00 | 4.82 |
| 50.0% | median | 55.00 | 25.000 | 20.000 | 28.000 | 48.00 | 1.95 |
| 25.0% | quartile | 37.00 | 20.000 | 13.000 | 19.700 | 17.00 | 0.50 |
| 10.0% | | 26.00 | 19.000 | 8.000 | 12.620 | 8.16 | 0.20 |
| 2.5% | | 23.00 | 17.000 | 2.000 | 2.205 | 4.00 | 0.10 |
| 0.5% | | 23.00 | 15.000 | 2.000 | 0.000 | 2.88 | 0.0763 |
| 0.0% | minimum | 23.00 | 15.000 | 2.000 | 0.000 | 2.00 | 0.04 |

**Moments**

| | LL | PL | PI | MC as tested wt% | Trafficability Cone Index | Field CBR |
|---|---|---|---|---|---|---|
| Mean | 55.259336 | 28.746888 | 26.512448 | 30.994296 | 95.790778 | 3.3552313 |
| Std Dev | 22.685529 | 12.331114 | 17.107853 | 16.55371 | 124.42931 | 7.1482702 |
| Std Err Mean | 1.0332975 | 0.5616669 | 0.7792414 | 0.6988982 | 5.2912726 | 0.3015316 |
| upper 95% Mean | 57.289671 | 29.850512 | 28.043586 | 32.367078 | 106.18427 | 3.9475001 |
| lower 95% Mean | 53.229001 | 27.643264 | 24.98131 | 29.621514 | 85.397285 | 2.7629625 |
| N | 482 | 482 | 482 | 561 | 553 | 562 |

Figure C16. SM soil type: range of values for Atterberg limits, moisture content, trafficability cone index, and field CBR.

# Appendix D: Additional Regression Analysis Equations and Graphs

## *CBR = a + b(CI)^c*

Regression analysis table of coefficients and graphs for the equation of the form

$$CBR = a + b(CI)^c \,. \tag{D1}$$

Table D1. Coefficients for initial exponential equations.

| Soils Type | USCS Classification | Coefficients | | | $R^2$ |
|---|---|---|---|---|---|
| | | *a* | *b* | *c* | |
| | CH | –1.63462035 | 0.686080639 | 0.429374997 | 0.8035 |
| | CL | –1.22094966 | 0.368299769 | 0.545342184 | 0.8866 |
| | MH | –0.95392315 | 0.276153413 | 0.539104503 | 0.7808 |
| | ML | –3.14595803 | 0.928789277 | 0.430012159 | 0.5680 |
| | SM | –7.60469356 | 9.826607694 | 0.074386815 | 0.0612 |
| | GP | –31.4829214 | 24.68279433 | 0.121810957 | 0.5248 |
| Coarse-grained | SM + GP | 0.851525079 | 0.707683834 | 0.580775420 | 0.3500 |
| Fine-grained | CH, CL, MH, ML | –1.37924971 | 0.485100981 | 0.483650036 | 0.7725 |
| High plasticity | CH + MH | –1.76349771 | 0.757343985 | 0.399824150 | 0.7653 |
| Low plasticity | CL + ML | –1.48393600 | 0.438444720 | 0.522076596 | 0.8175 |

The following graphs are for soil types CH, CL, MH, ML, SM, and GP:

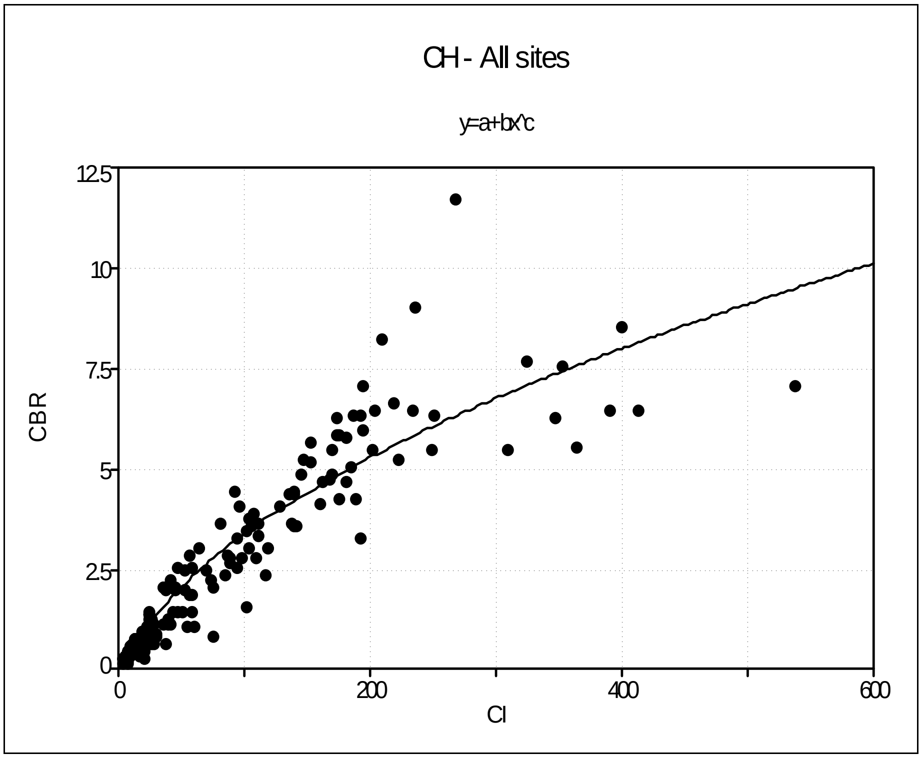



Figure D1. CBR versus CI for soil type CH.

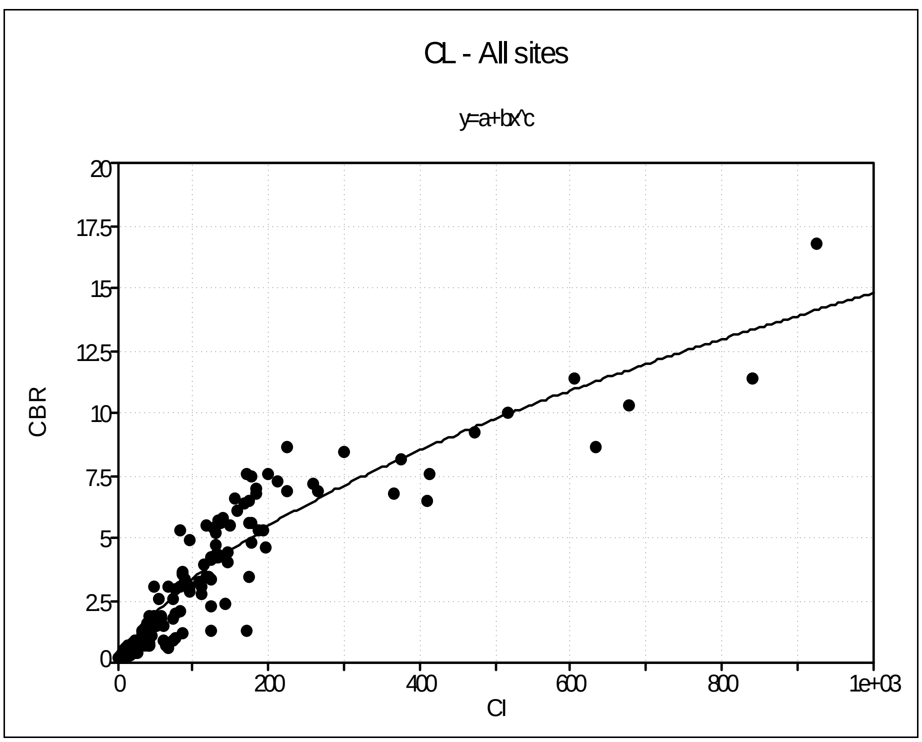



Figure D2. CBR versus CI for CL soils.

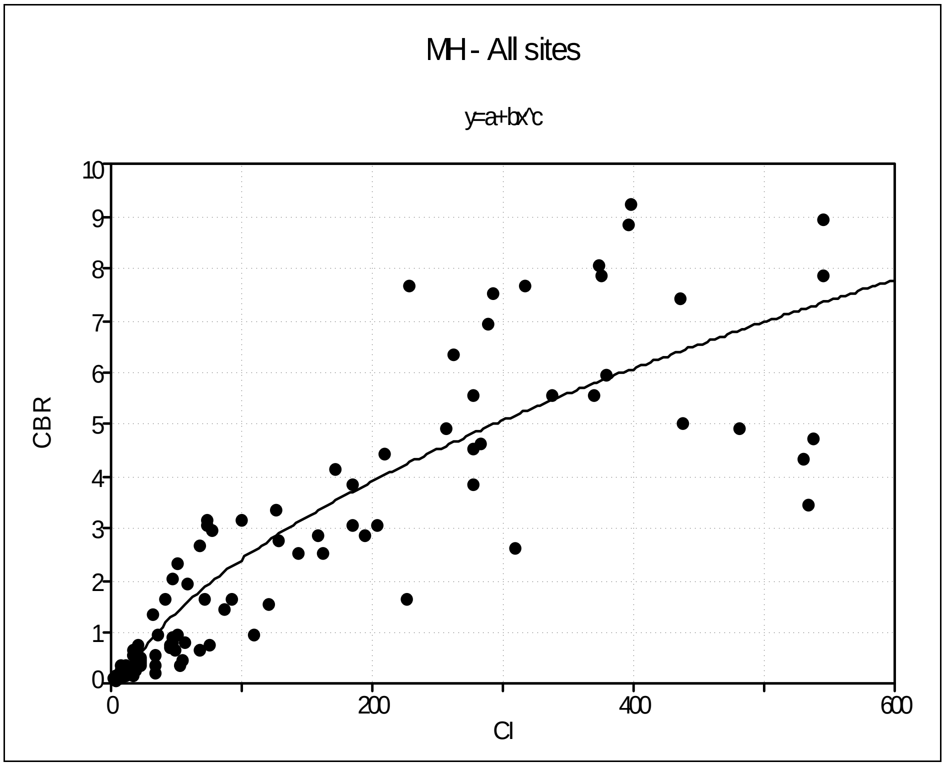



Figure D3. CBR versus CI for MH soils.

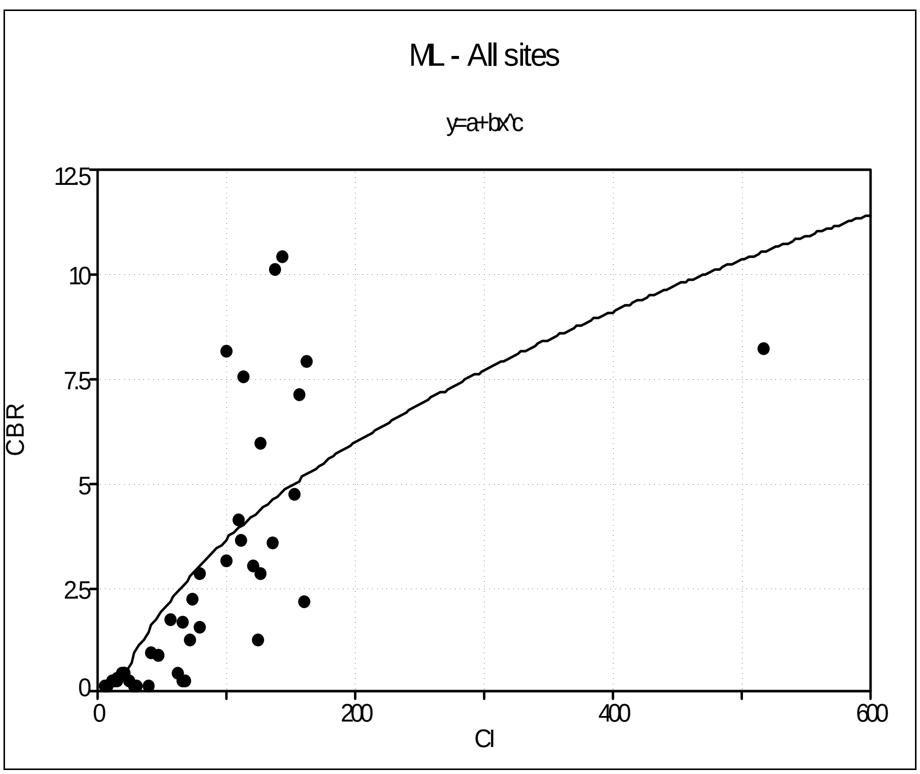



Figure D4. CBR versus CI for soil type ML.

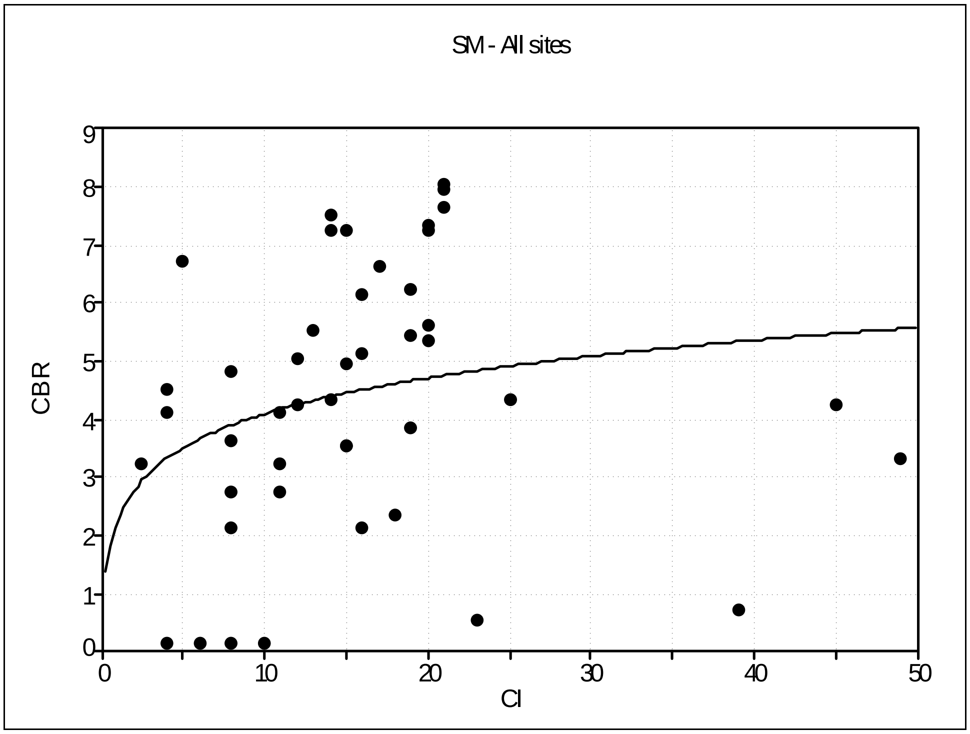



Figure D5. CBR versus CI for SM soils.

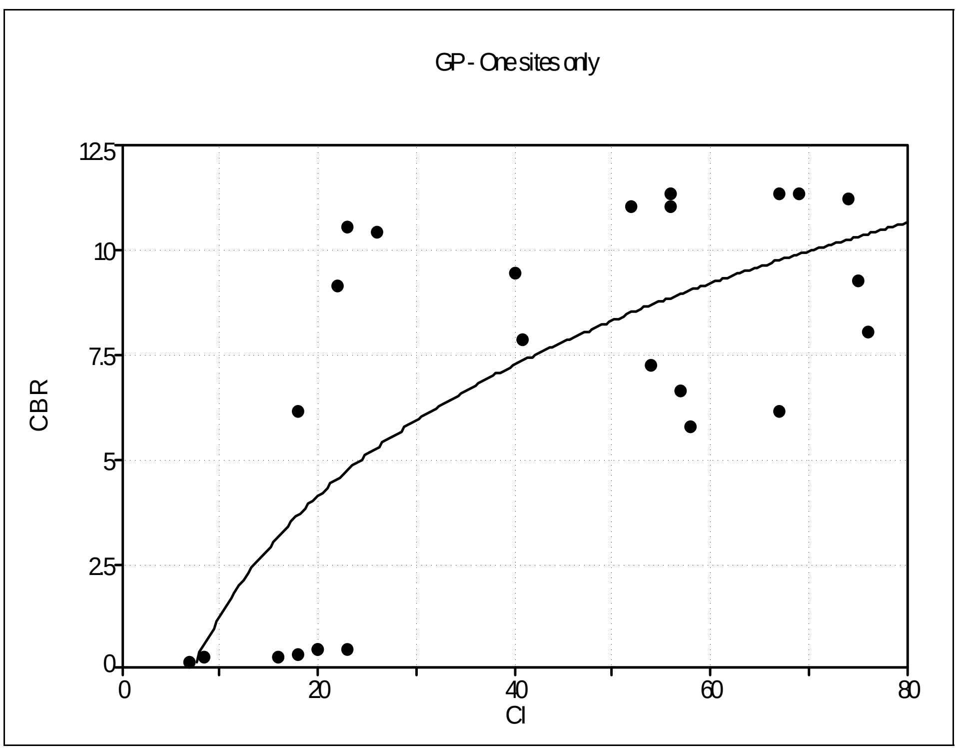



Figure D6. CBR versus CI for GP soils.

The following graphs are for the soil subsets:

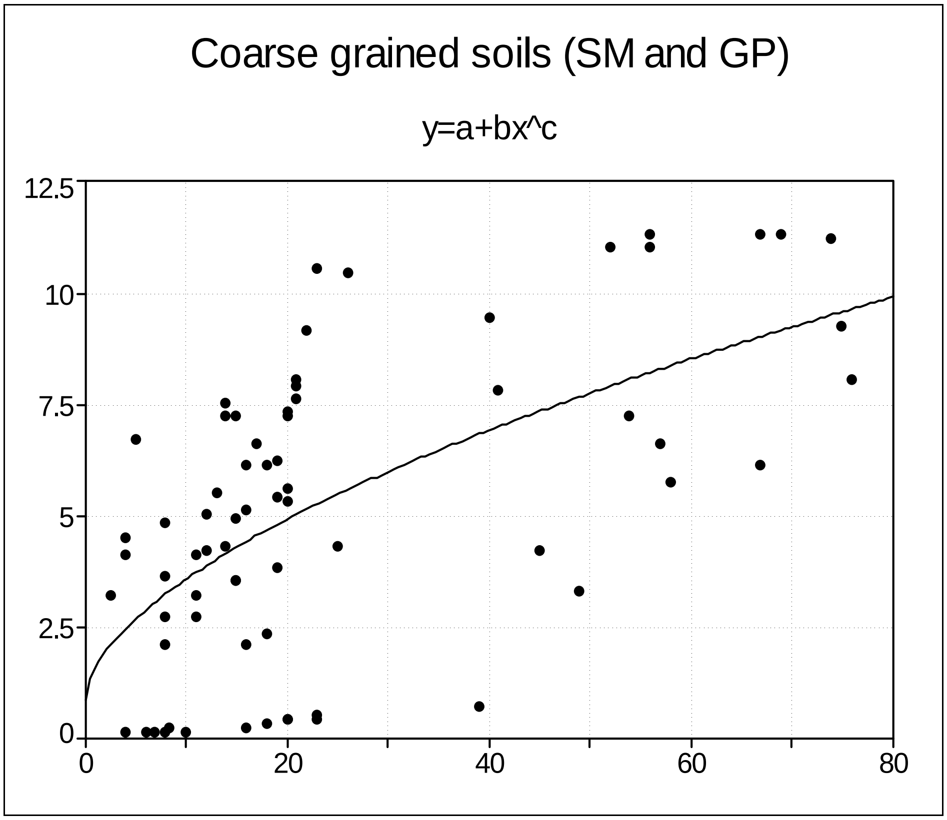



Figure D7. CBR versus CI for coarse-grained soils.

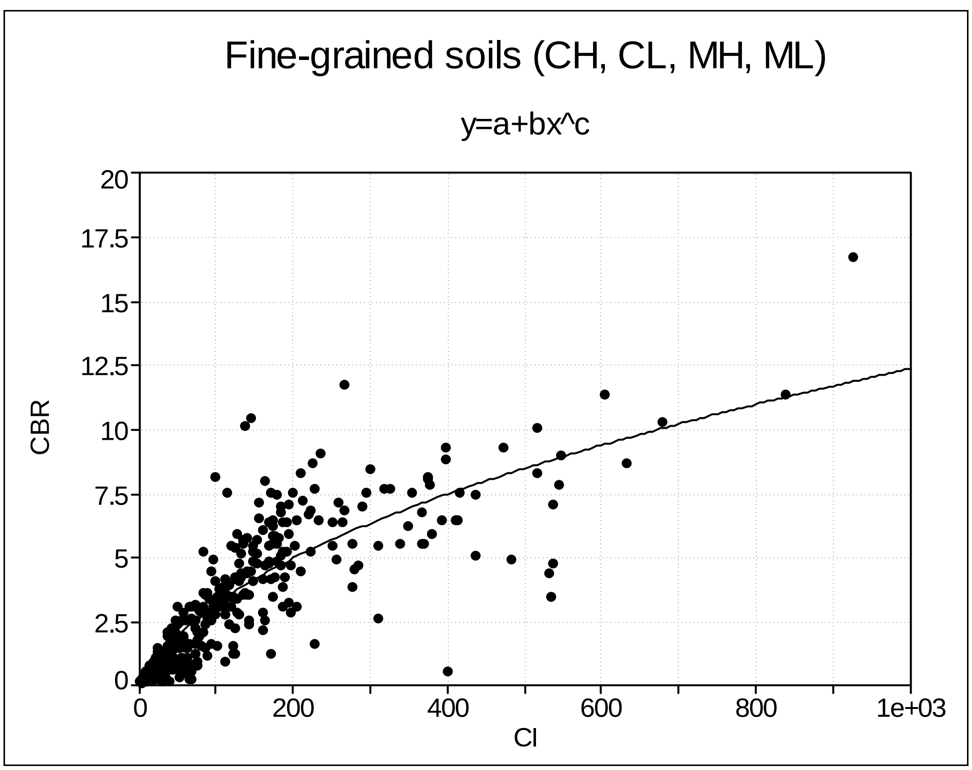



Figure D8. CBR versus CI for fine-grained soils.

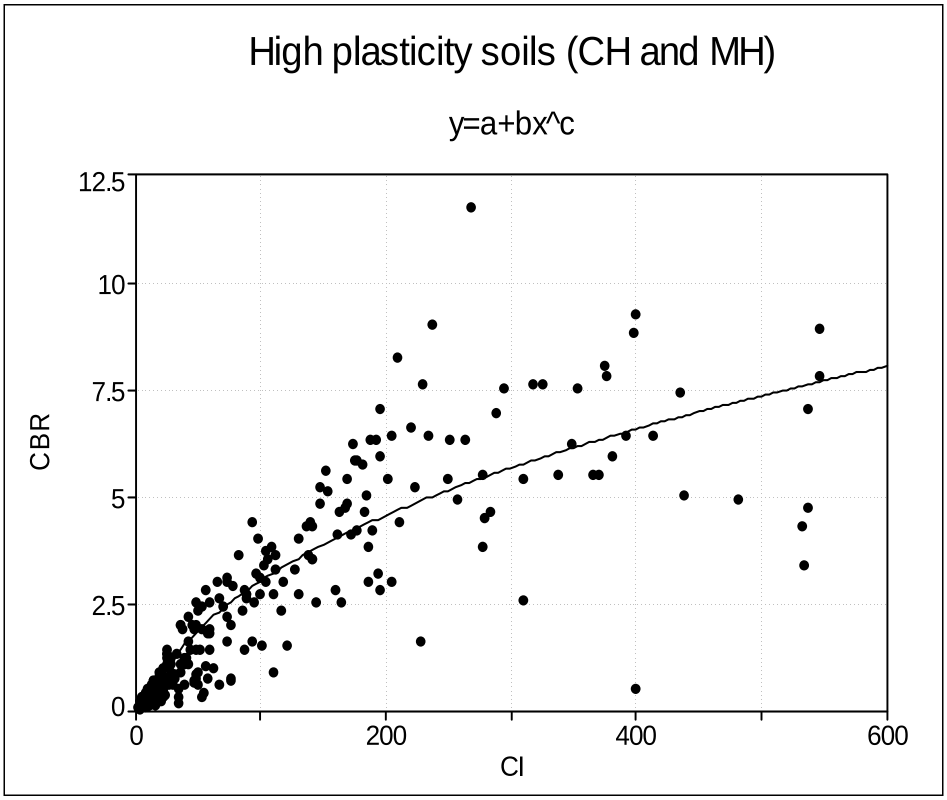



Figure D9. CBR versus CI for high-plasticity soils.

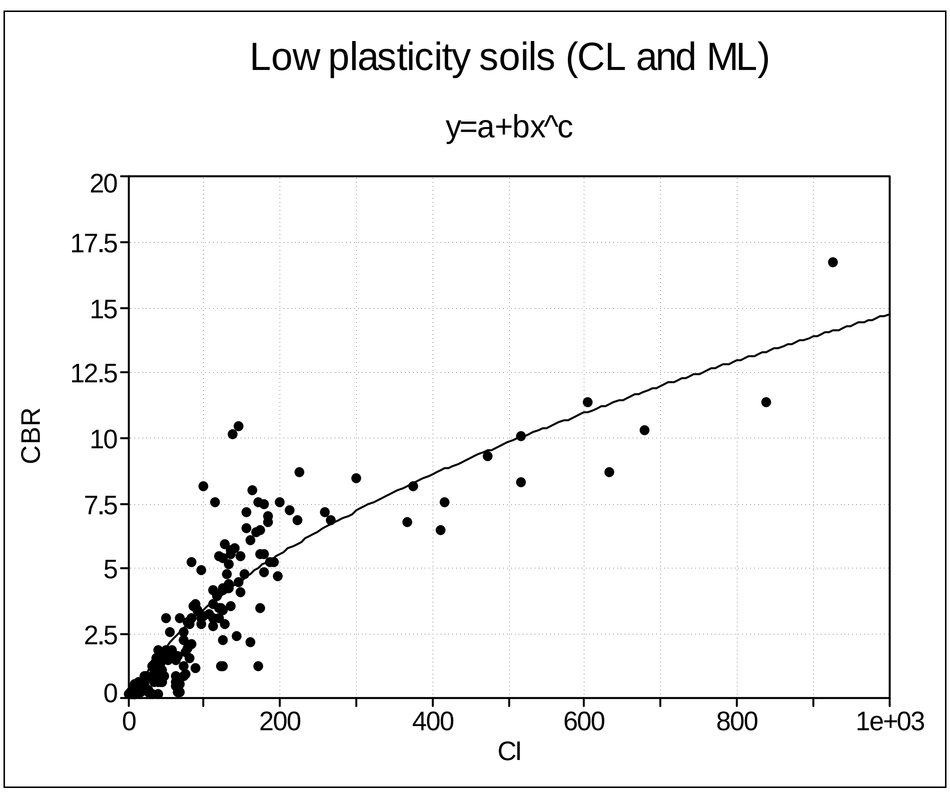



Figure D10. CBR versus CI for low-plasticity soils.

## *CBR = a(CI)^b*

Regression analysis table of coefficients and graphs for the equation of the form:

$$CBR = a(CI)^b \,. \tag{D2}$$

These data are by soil type, and by individual site. In addition, for the MH soil, the data are divided into two groups, one with higher CBR, and one with lower CBR.

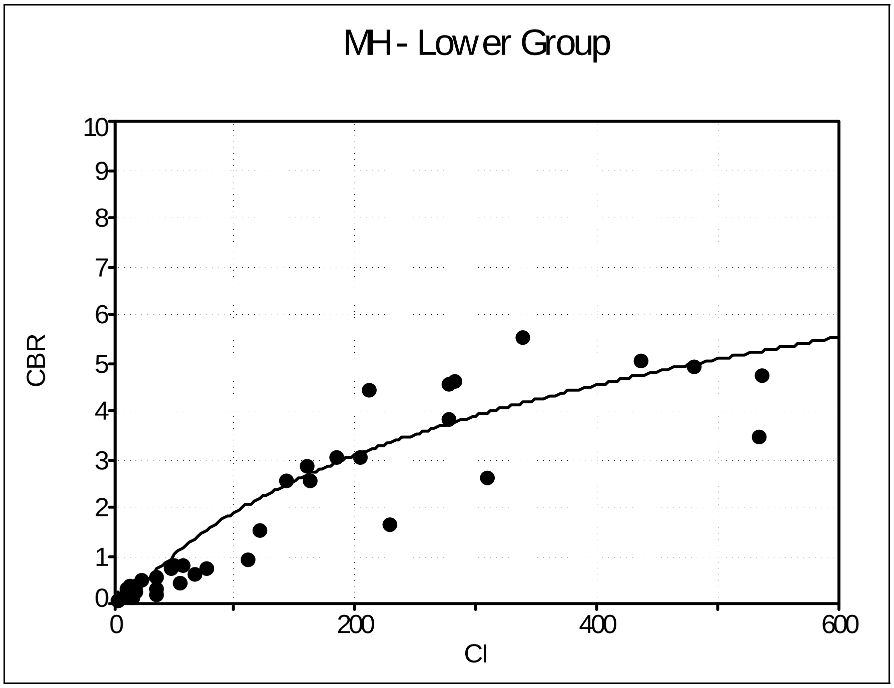
Table D2. MH soils regression coefficients.

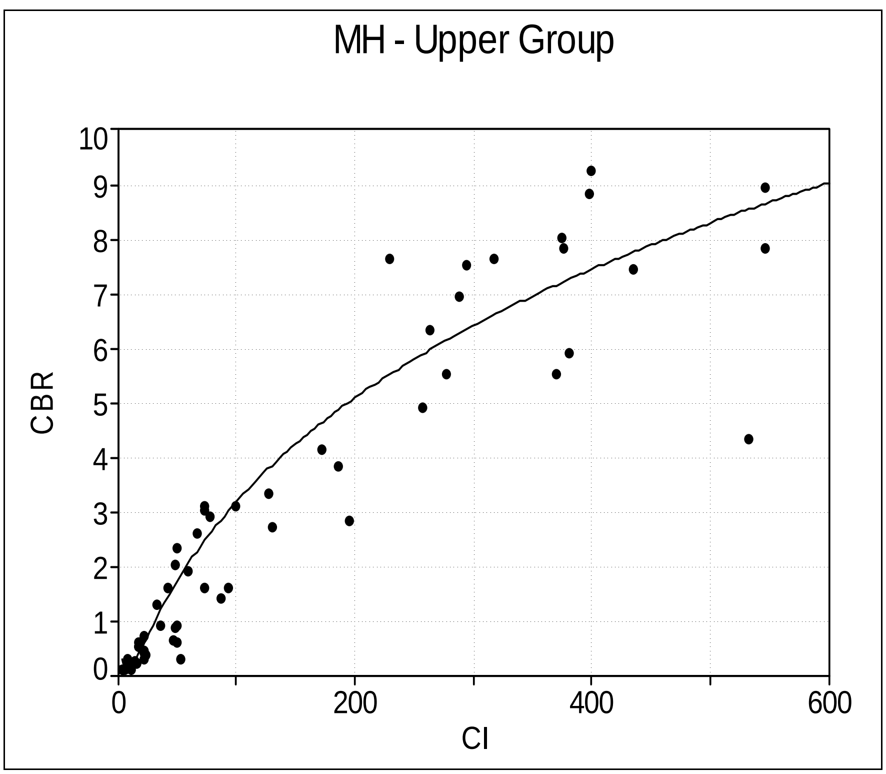
| Soil Type | Coefficients | | $R^2$ | Dry Density pcf | MC wt % | Plasticity | | |
|---|---|---|---|---|---|---|---|---|
| | *a* | *b* | | | | LL | PL | PI |
| All MH | 0.0820 | 0.7174 | 0.7715 | 70.9 | 47.4 | | | |
| MH Lower group* | 0.0592 | 0.7154 | 0.8280 | 67.0 | 53.4 | | | |
| MH Upper group** | 0.1002 | 0.7123 | 0.8672 | 74.4 | 43.7 | | | |
| Lower Group | | | | | | | | |
| MH Ramey | 0.1159 | 0.6111 | 0.9337 | 74.3 | 42.2 | 65 | 34 | 31 |
| MH Wahiawa | 0.0498 | 0.7712 | 0.8507 | 72.0 | 44.1 | 64 | 46 | 18 |
| MH Mayaguez | 0.2206 | 0.4798 | 0.7502 | 83.0 | 36.6 | 58 | 38 | 20 |
| MH Wainaku | 0.0277 | 0.8081 | 0.8806 | 55.7 | 72.7 | 96 | 76 | 20 |
| MH Tillamook | 0.0145 | 0.9605 | 0.7743 | 53.4 | 68.1 | 89 | 77 | 12 |
| Upper Group | | | | | | | | |
| MH Clayton | 0.1444 | 0.6308 | 0.7817 | 78.9 | 37.4 | 67 | 49 | 18 |
| MH Yabucoa | 0.0271 | 0.9608 | 0.9870 | 73.9 | 43.4 | 77 | 39 | 38 |
| MH Chanthaburi | 0.0220 | 0.9551 | 0.9863 | 74.5 | 44.5 | 53 | 42 | 11 |
| MH Barcelometa | 0.0234 | 1.0030 | 0.9019 | 72.7 | 43.1 | 76 | 48 | 28 |
| MH P. Miguel | 0.0253 | 0.9618 | 0.9163 | 70.1 | 47.1 | 76 | 44 | 32 |
| MH Port Hueneme | 0.0418 | 0.9704 | 0.9567 | | 46.4 | 72 | 41 | 31 |

* Lower group: Tillamook, Mayaguez, Ramey, Wainaku, Wahiawa.

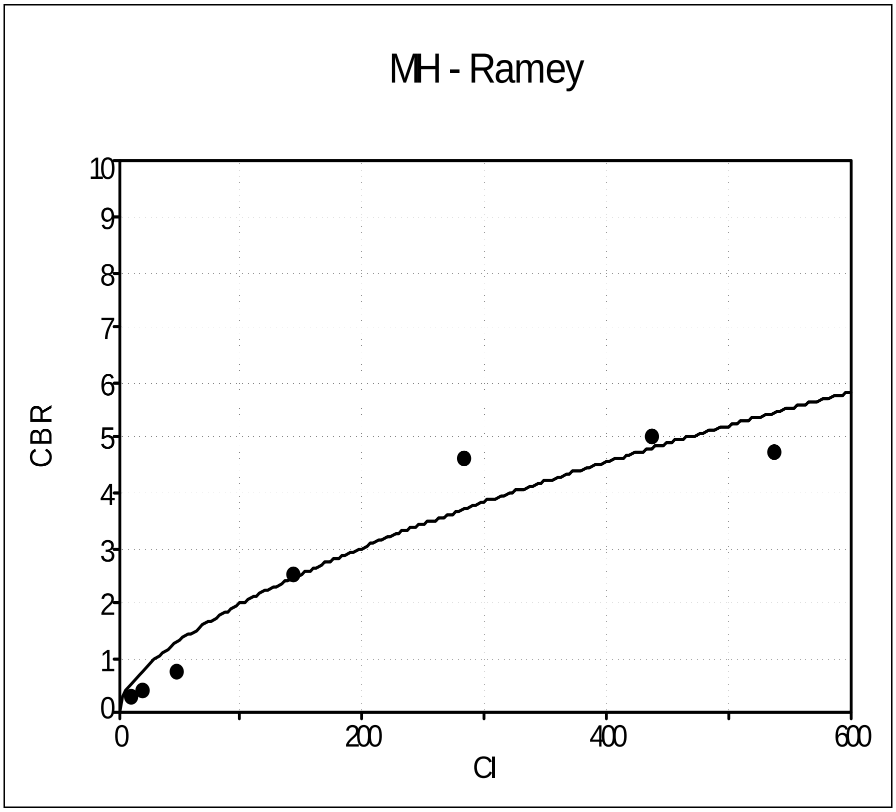
** Upper group: Pedro Miguel, Barcelometa, Port Hueneme, Yabucoa, Clayton, Chanthaburi.

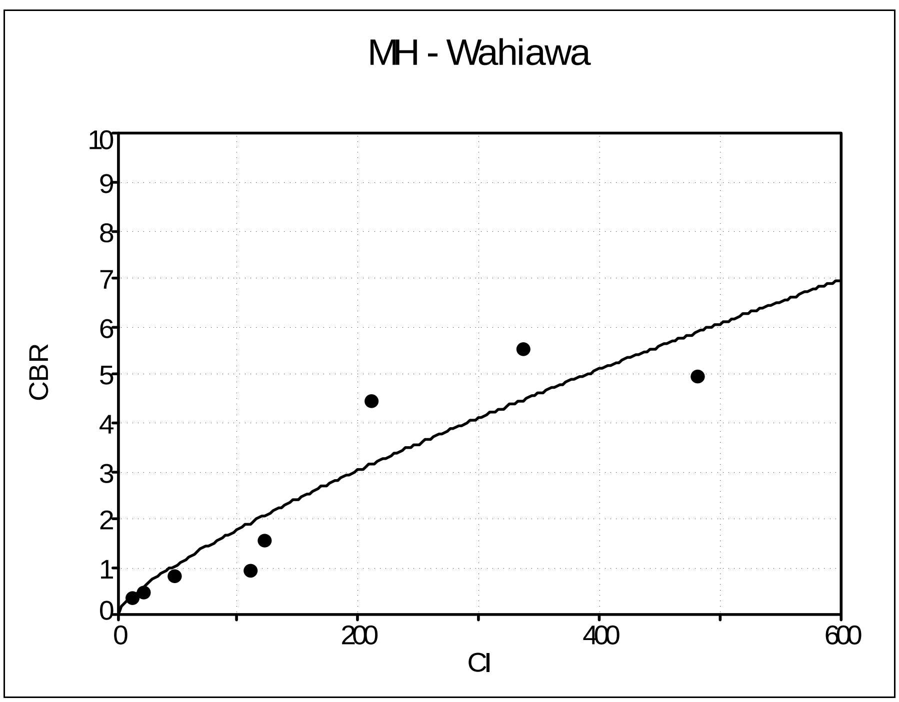
## Grouped sites

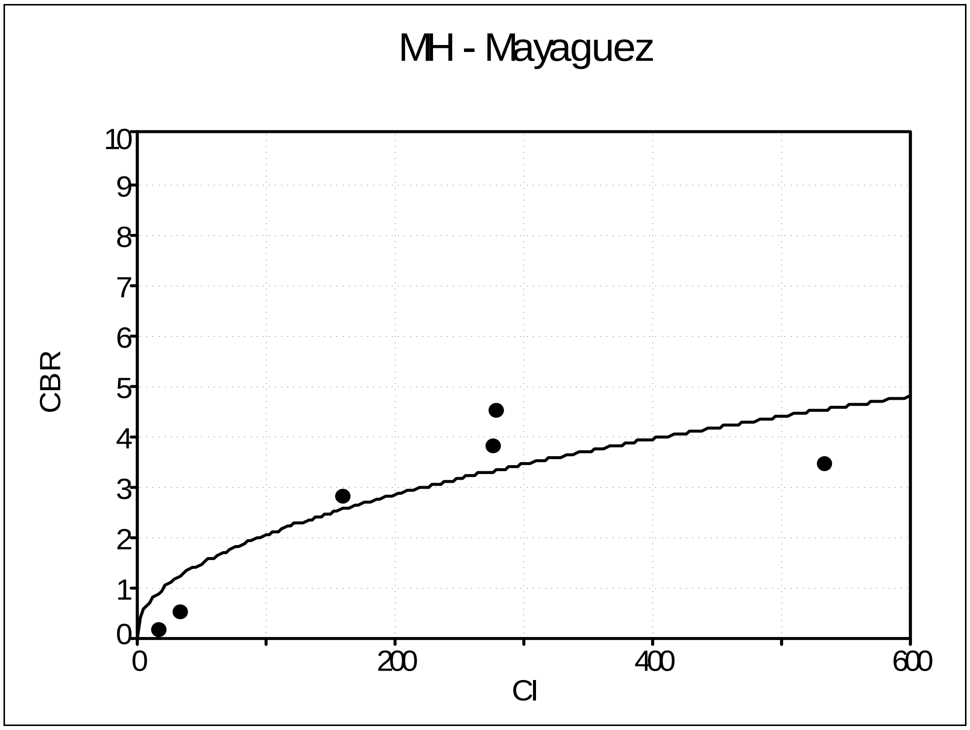


## Individual sites

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CBR
CI
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200
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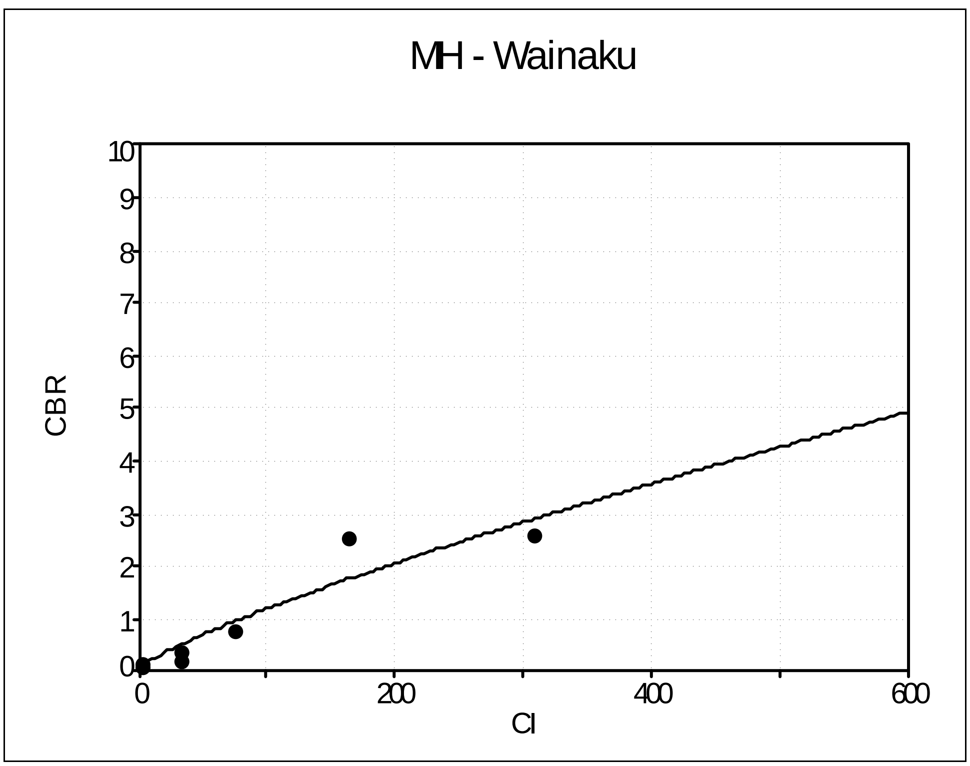
600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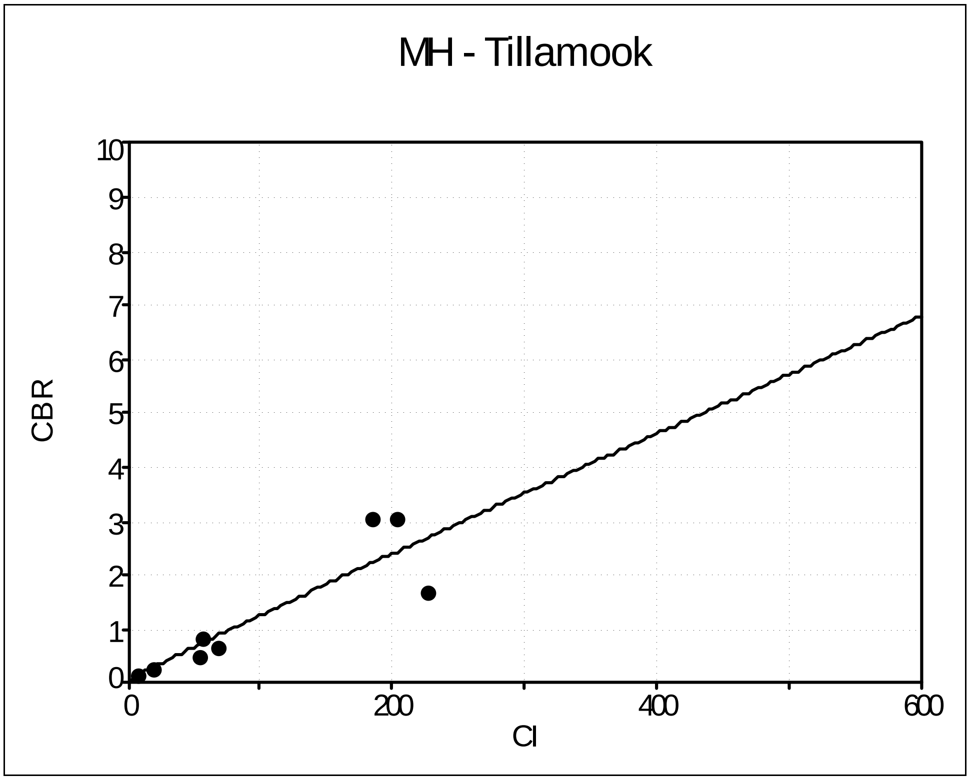
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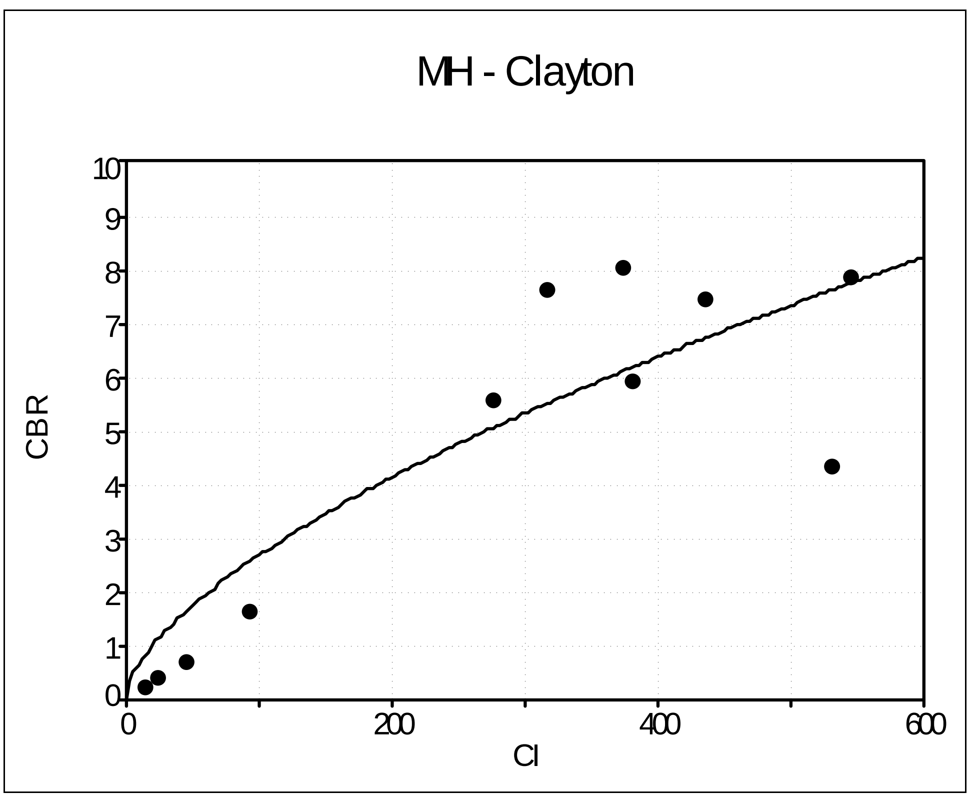
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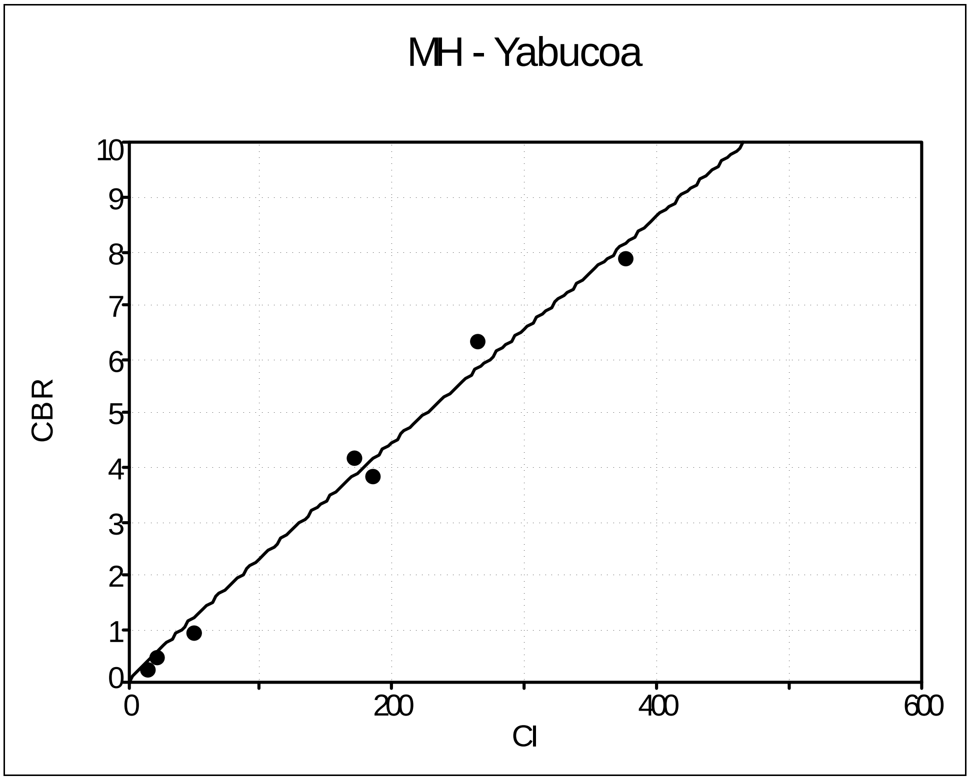
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CI
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400
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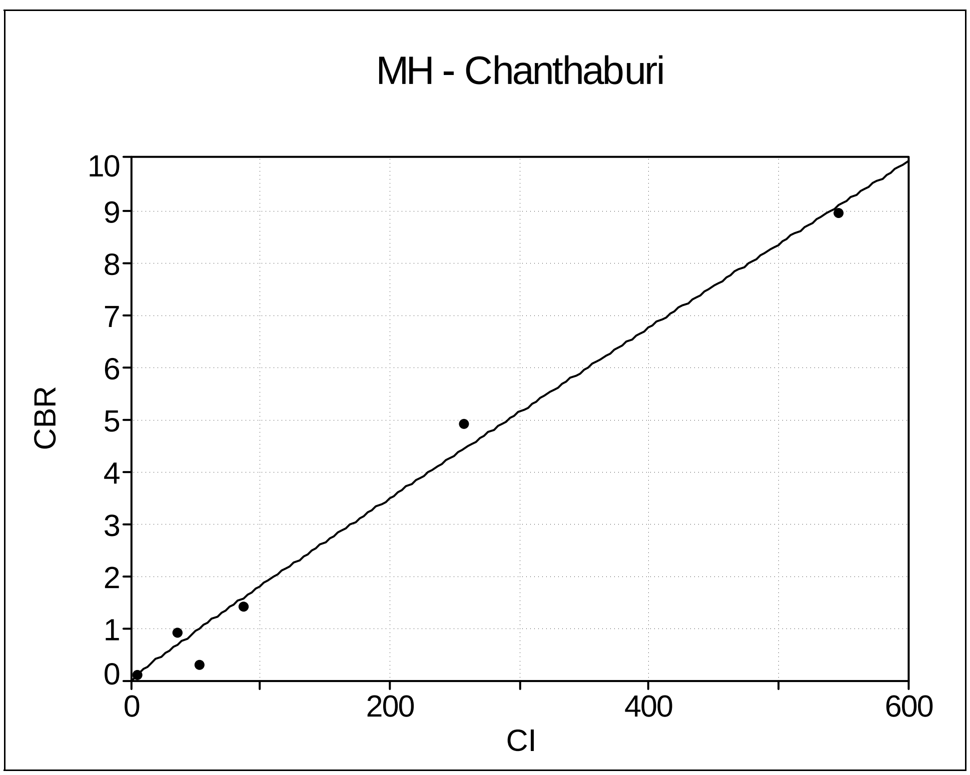
MH - Chanthaburi
CBR
CI
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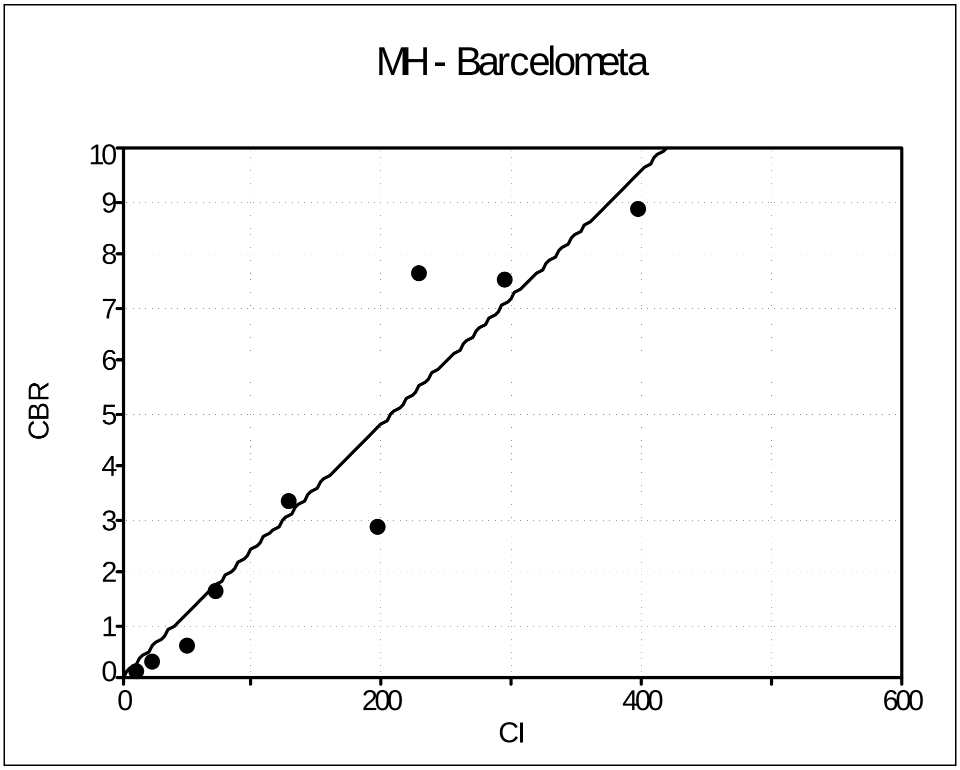
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CI
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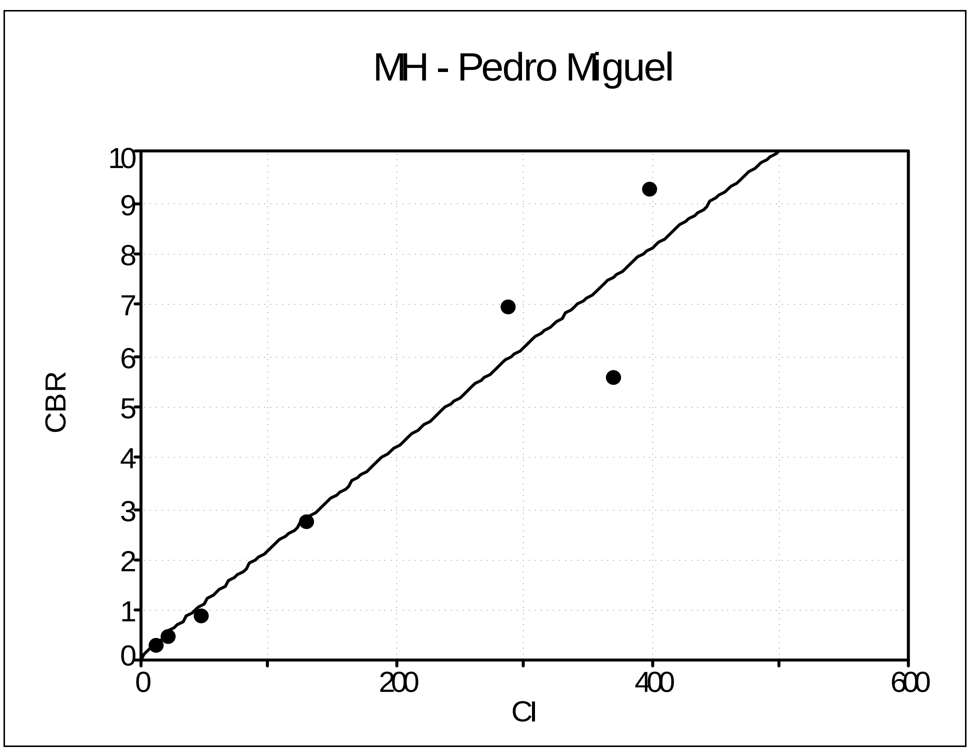
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CBR
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400
600

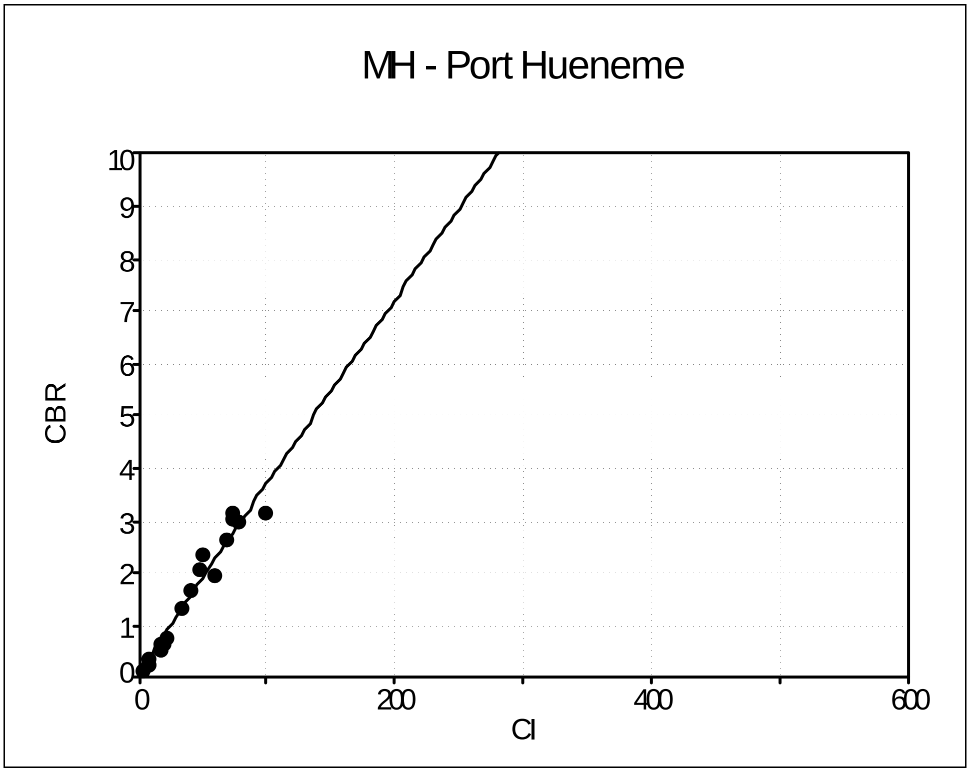
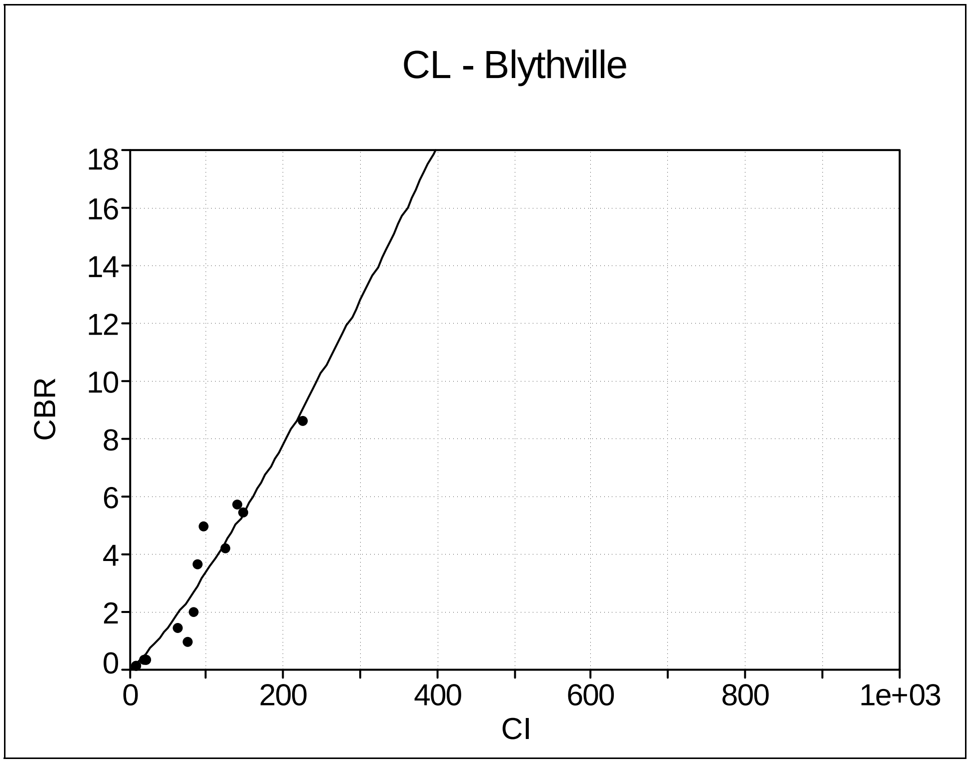
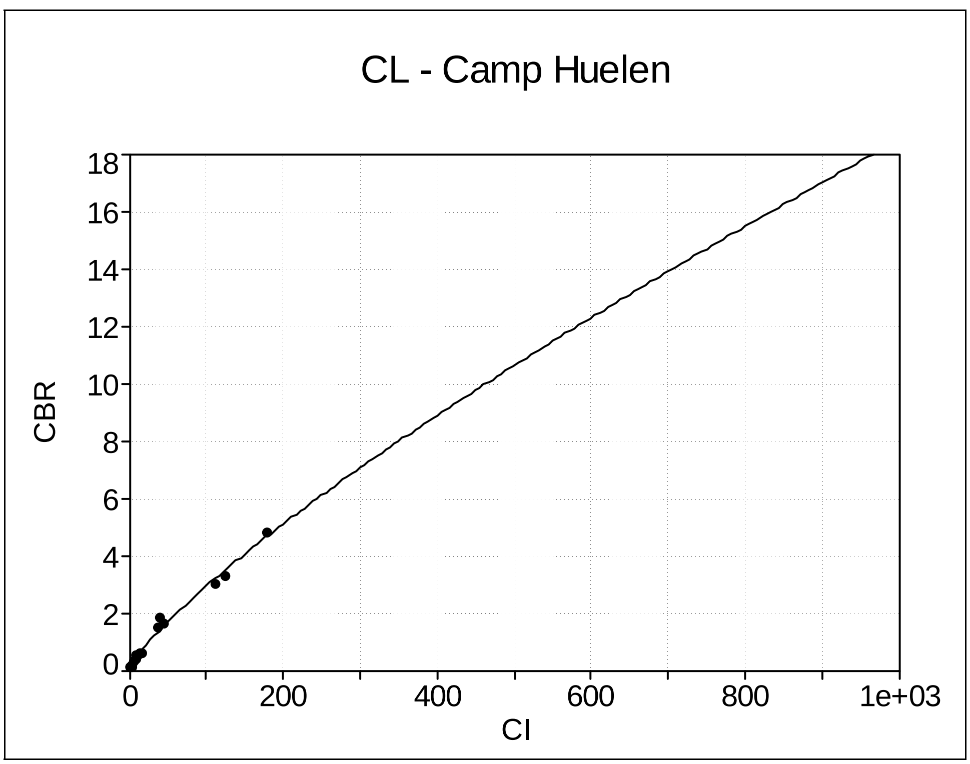


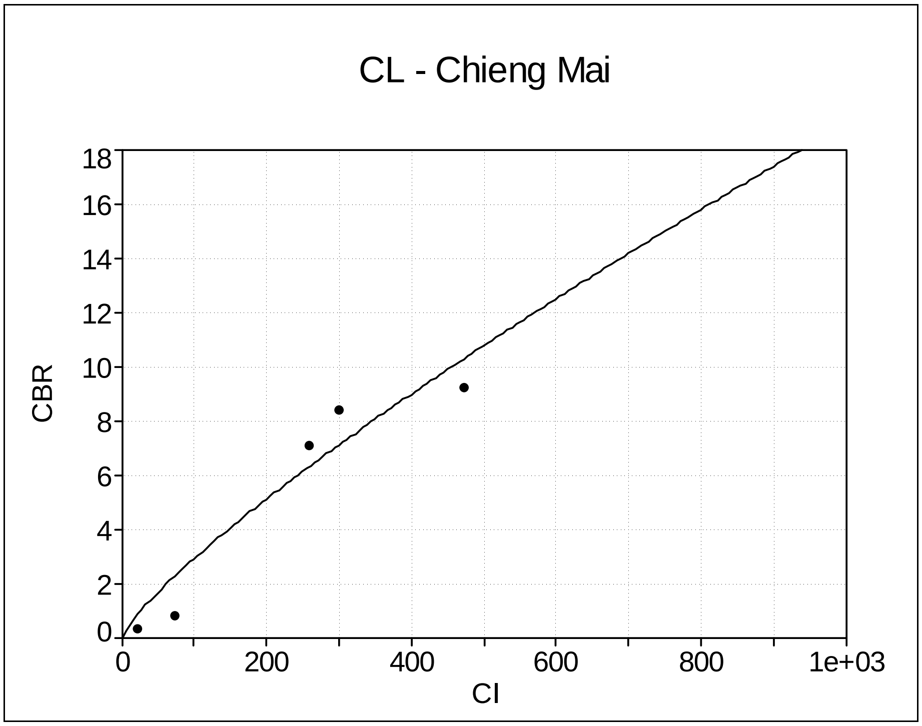

Table D3. CL Soils regression coefficients.

| Soil Type | Coefficients | | $R^2$ | Dry Density | MC wt % | Plasticity | | |
|---|---|---|---|---|---|---|---|---|
| | *a* | *b* | | | | LL | PL | PI |
| All CL | 0.1266 | 0.6986 | 0.8701 | 99.8 | 23.7 | | | |
| CL Blythville | 0.0121 | 1.2201 | 0.9315 | | 21.2 | 25 | 17 | 8 |
| CL Camp Huelen | 0.8006 | 0.0733 | 0.9903 | | 31.4 | 45 | 18 | 27 |
| CL Chieng Mai | 0.0677 | 0.8154 | 0.9182 | 99.6 | 21.0 | 31 | 22 | 9 |
| CL Delta | 0.0242 | 1.0509 | 0.9739 | | 24.3 | 35 | 22 | 13 |
| CL Fort Kobbe | 0.0184 | 0.9589 | 0.9595 | 98.3 | 23.3 | 34 | 25 | 9 |
| CL Khon Kaen | 0.0102 | 1.0853 | 0.9964 | 110.4 | 14.3 | 23 | 15 | 8 |
| CL Newport | 0.0454 | 0.9371 | 0.9499 | | 25.1 | 40 | 20 | 20 |
| CL Oxford | 0.1591 | 0.6440 | 0.9404 | 93.6 | 23.6 | 39 | 22 | 17 |
| CL Shreveport | 0.0044 | 1.3919 | 0.8392 | | 17.3 | 27 | 19 | 8 |
| CL Stuttgart | 0.0366 | 0.9911 | 0.9566 | | 24.5 | 37 | 20 | 17 |
| CL Vicksburg 1 (aka Vicksburg, MS (Rifle Range)) | 0.0044 | 1.4202 | 0.7277 | | 26.1 | 39 | 25 | 14 |
| CL Vicksburg 2 (aka Vicksburg, MS) | 0.1258 | 0.6791 | 0.9623 | 99.8 | 20.9 | 34 | 22 | 12 |

## Individual sites




CL - Chieng Mai
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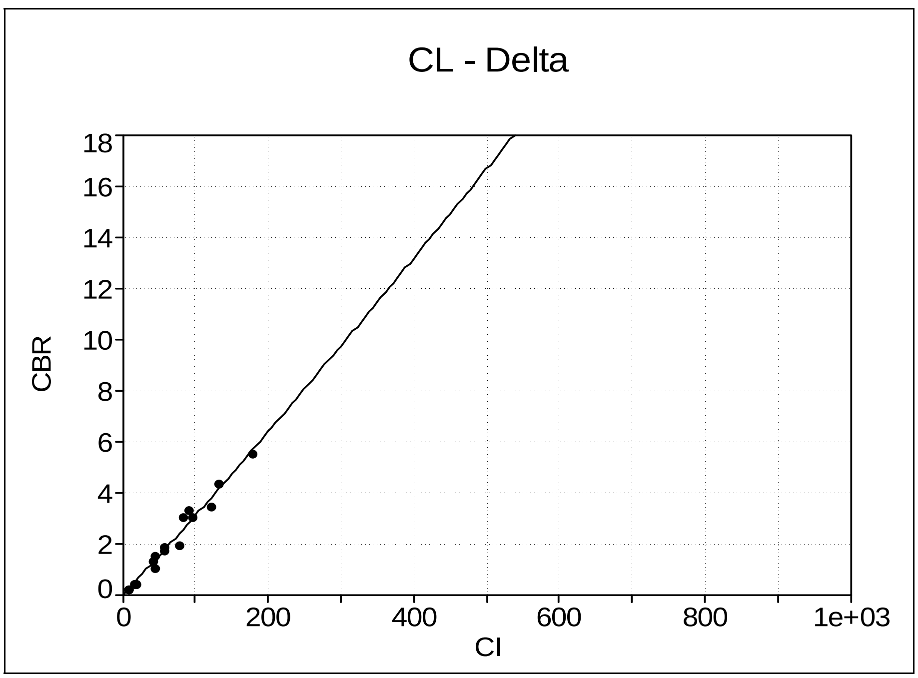
1e+03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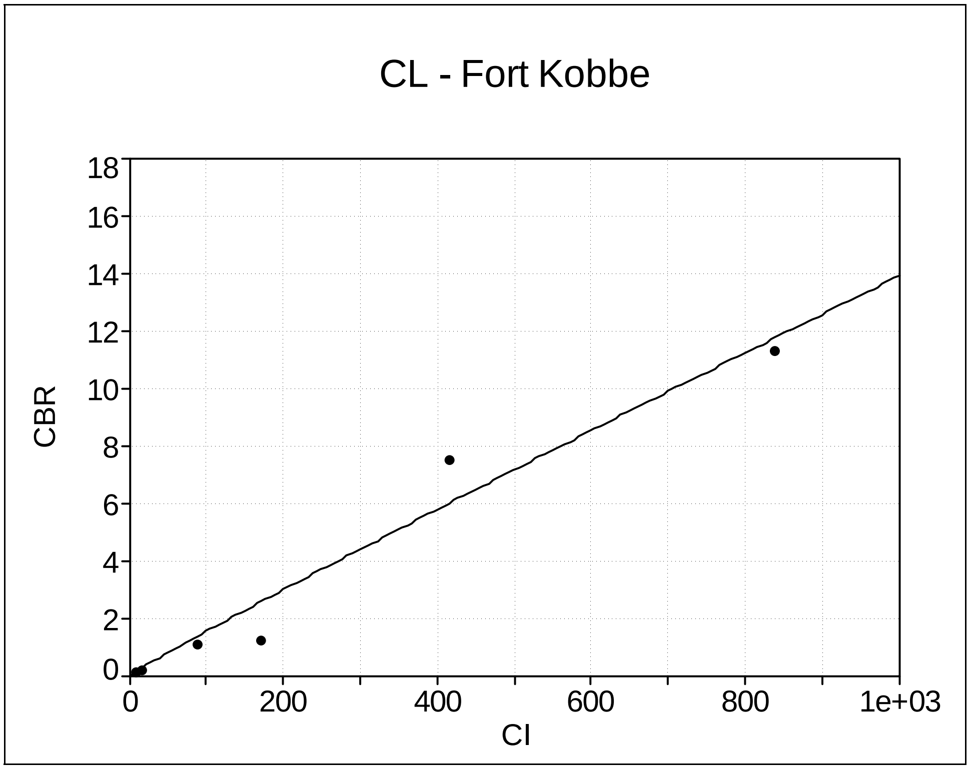
CL - Fort Kobbe
CBR
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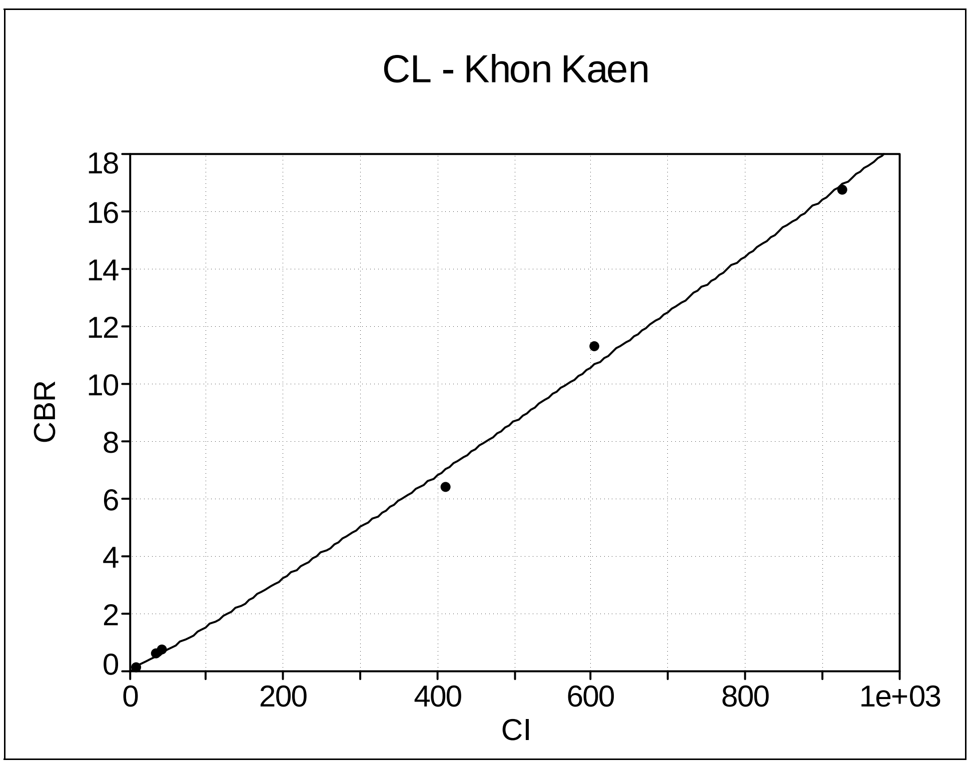
CL - Khon Kaen
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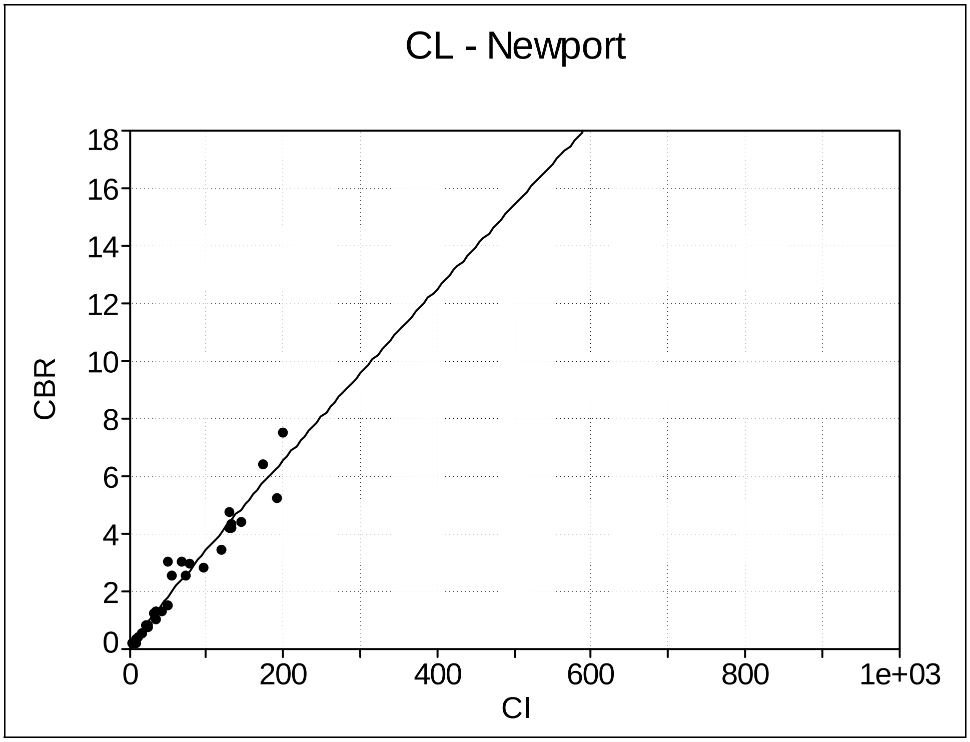
600
800
1e+03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CI
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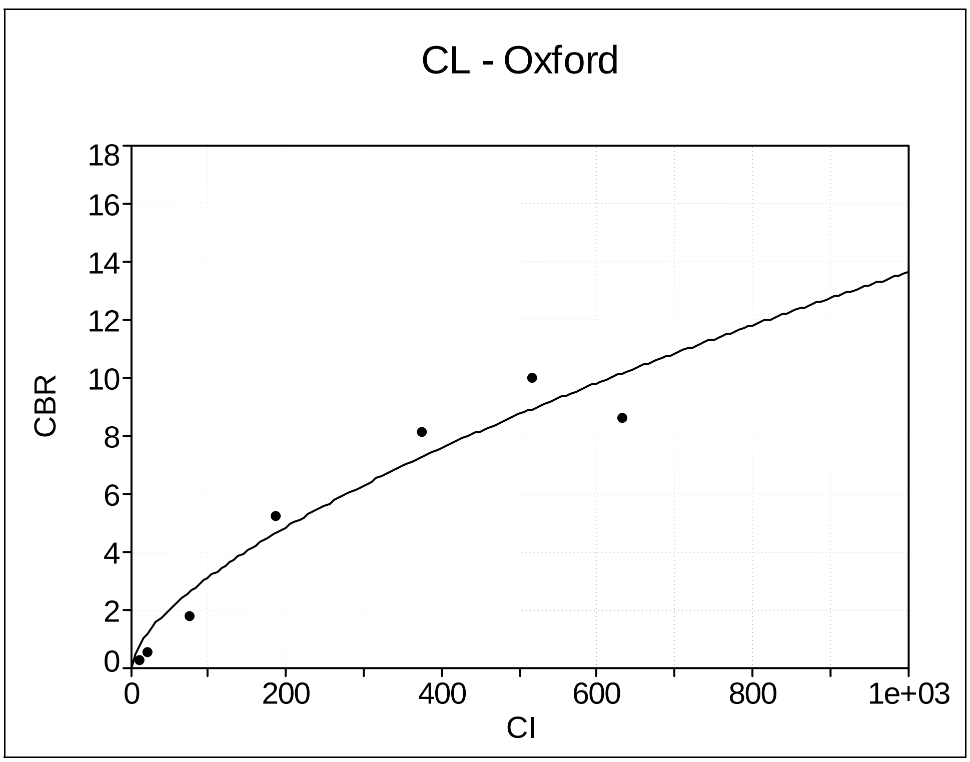
800
1e+03


CL - Oxford
CBR
CI
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4
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8
10
12
14
16
18
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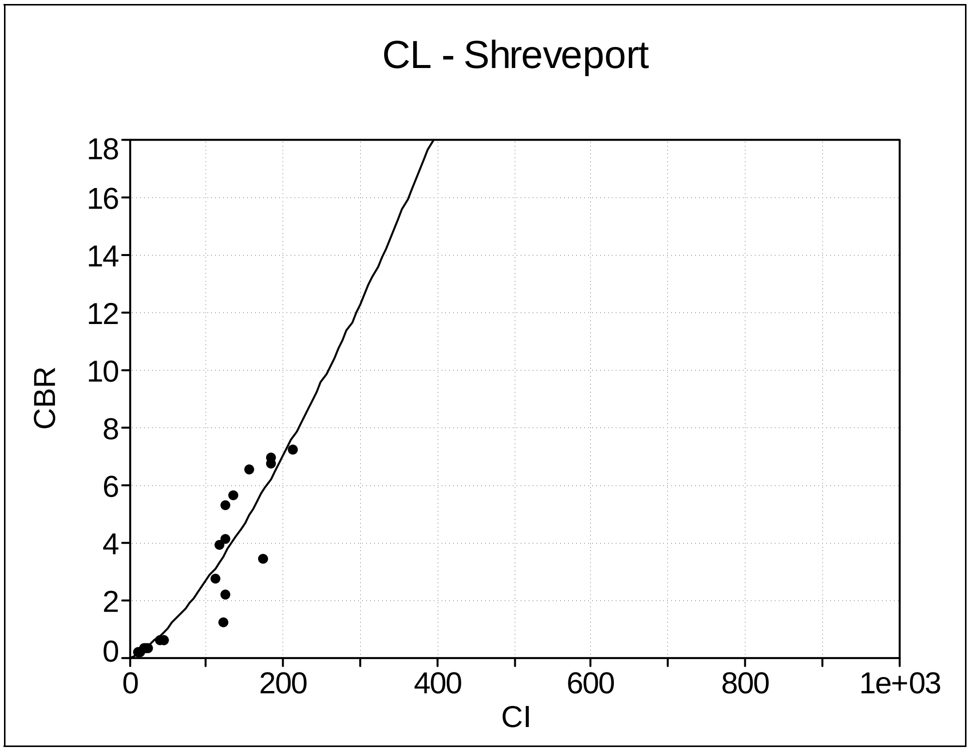
200
400
600
800
1e+03


CL - Shreveport
CBR
CI
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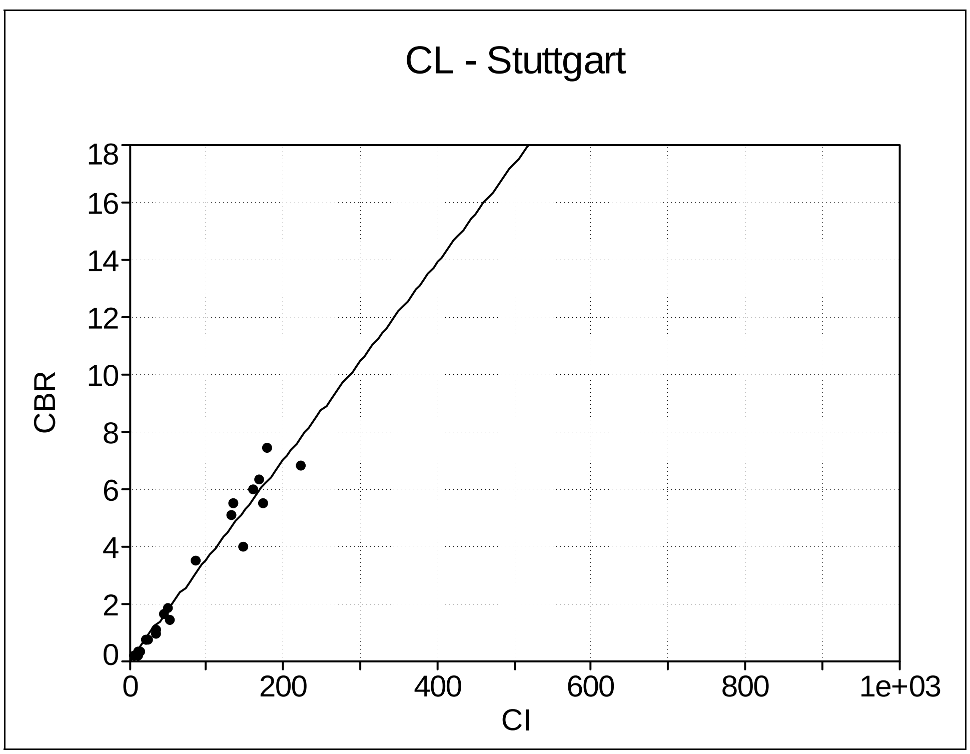
2
4
6
8
10
12
14
16
18
0
200
400
600
800
1e+03


CL - Stuttgart
CBR
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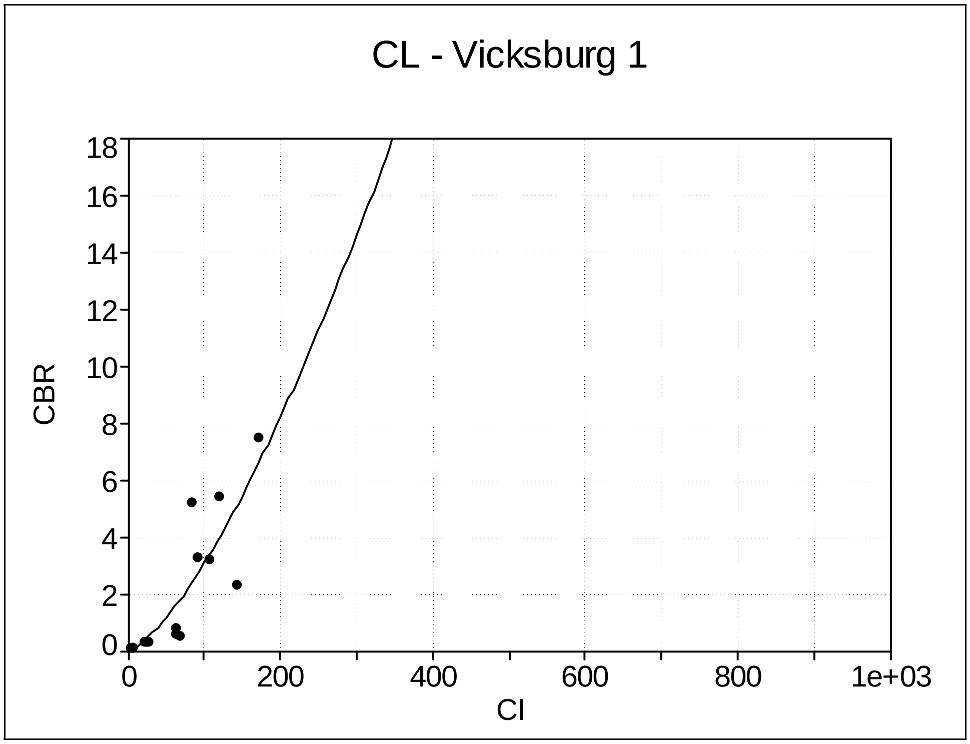
CL - Vicksburg 1
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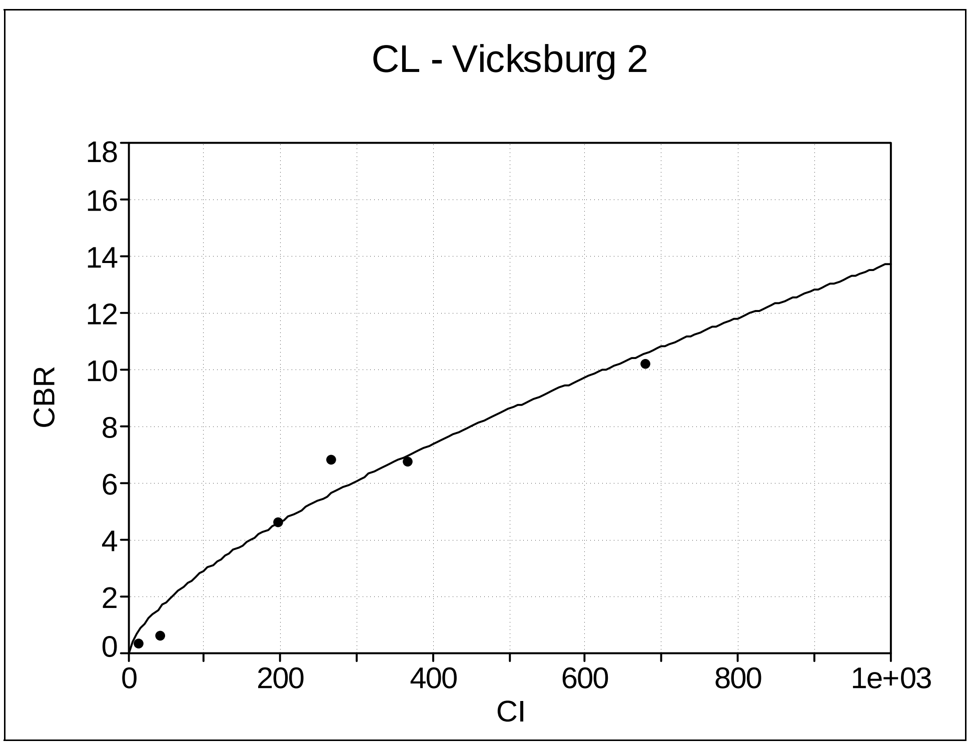
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CBR
CI
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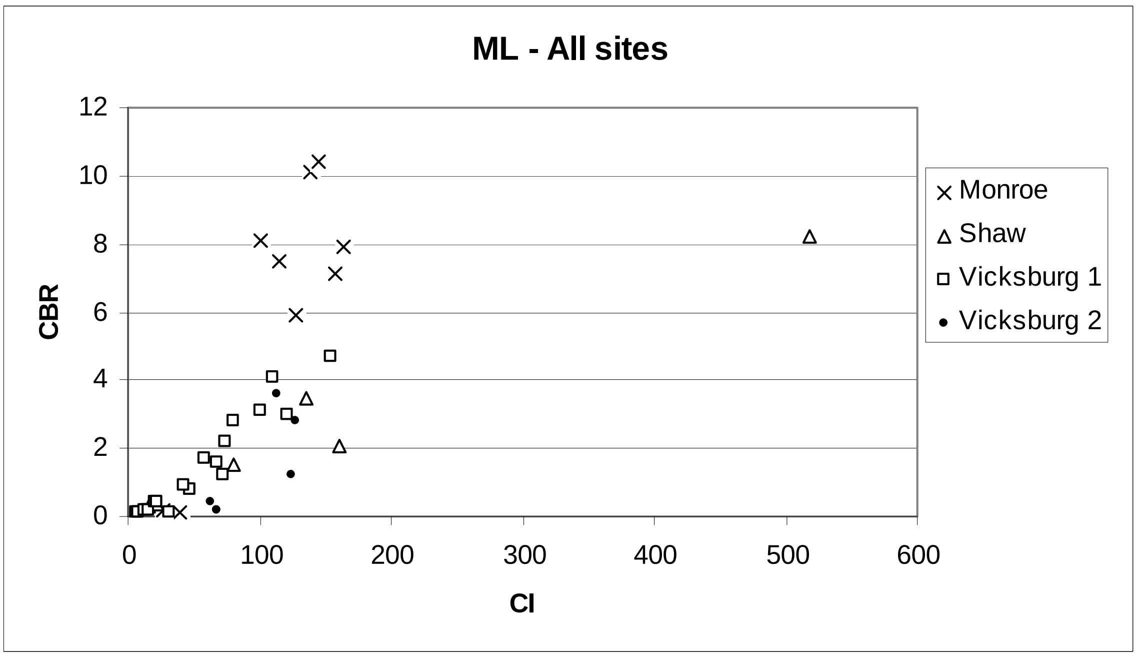
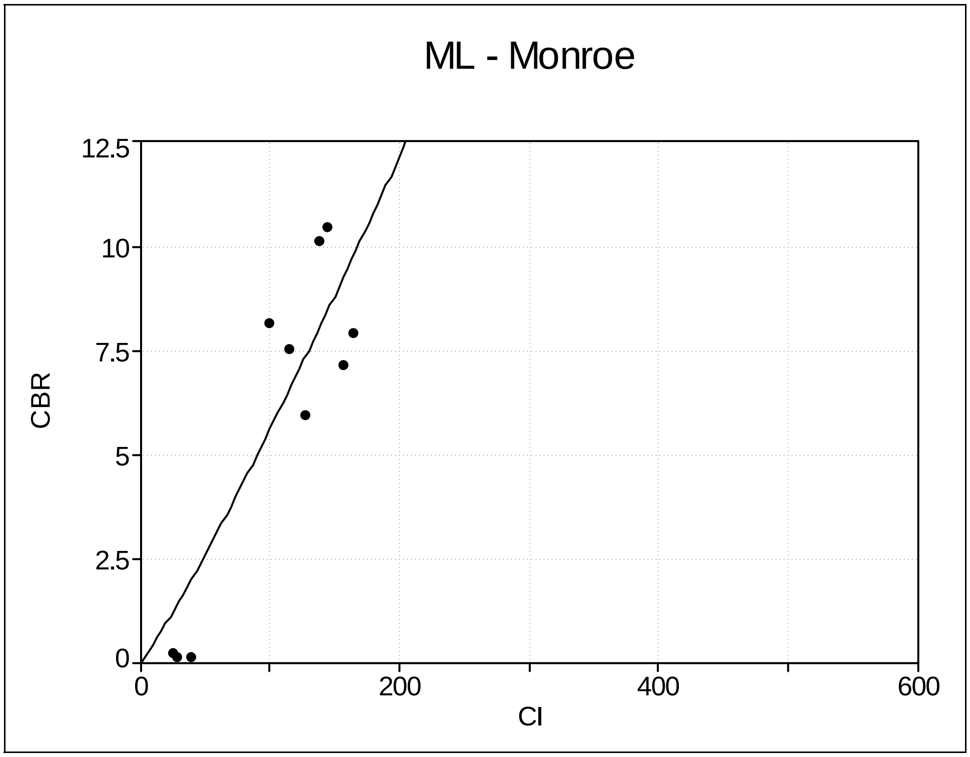
2
4
6
8
10
12
14
16
18
0
200
400
600
800
1e+03

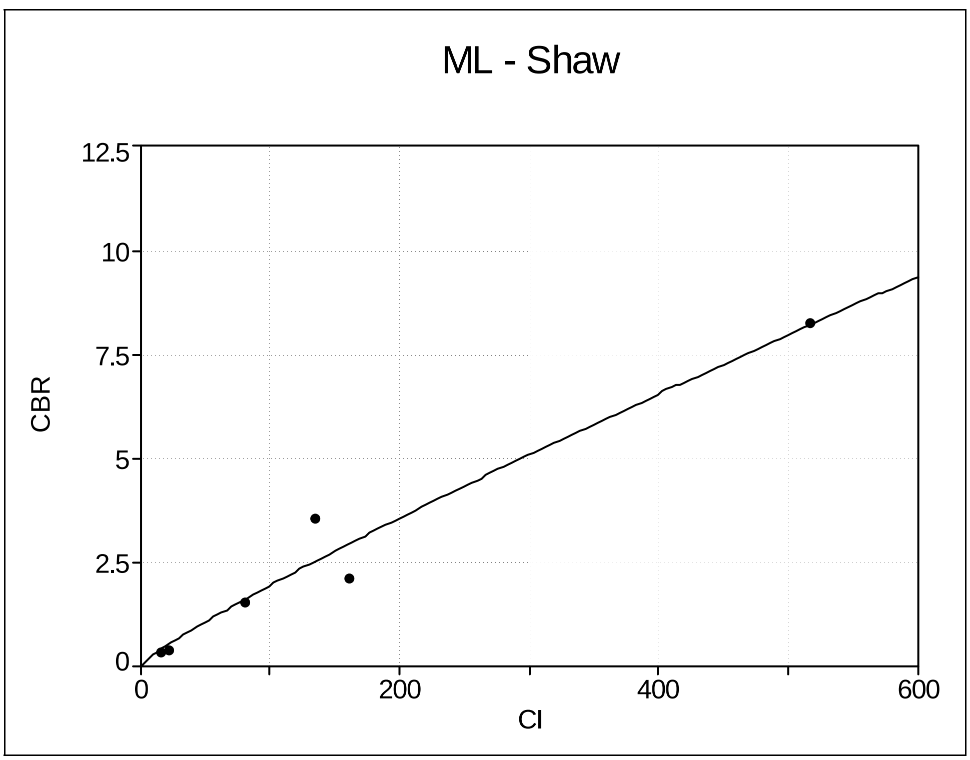
Table D4. ML soils regression coefficients.

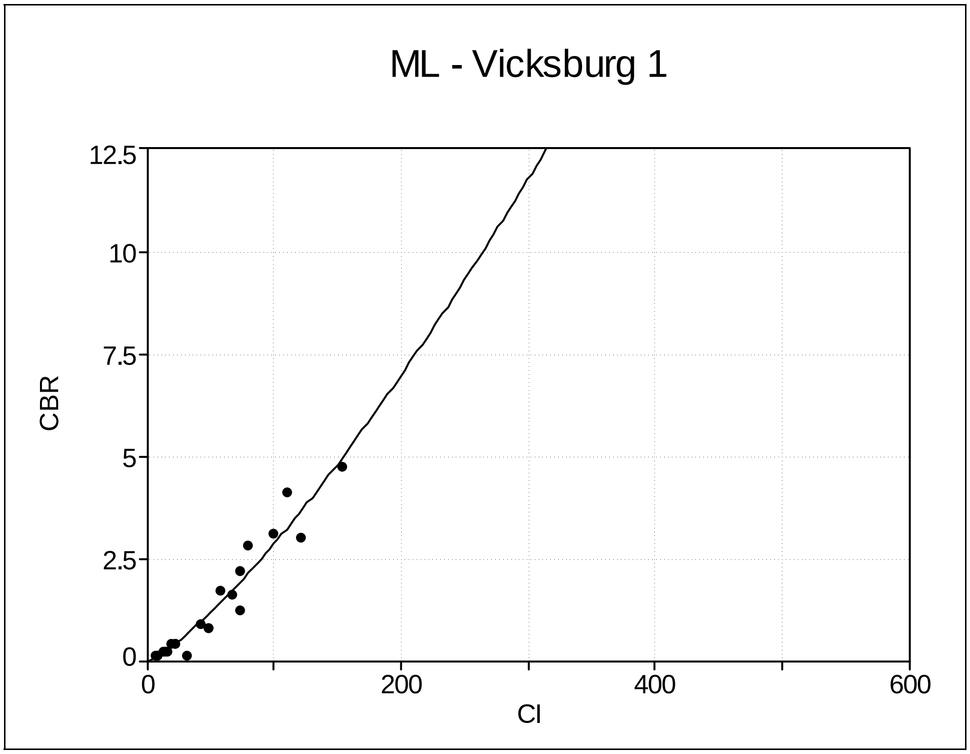
| Soil Type | Coefficients | | $R^2$ | Dry Density | MC | Plasticity | | |
|---|---|---|---|---|---|---|---|---|
| | *a* | *b* | | pcf | wt % | LL | PL | PI |
| All ML | 0.1111 | 0.7390 | 0.5193 | 88.8 | 23.6 | | | |
| ML Monroe | 0.0321 | 1.1194 | 0.7882 | | 19.4 | | | |
| ML Shaw | 0.0325 | 0.8844 | 0.9619 | 88.8 | 29.8 | 45 | 27 | 18 |
| ML Vicksburg 1 (aka Delta, LA) | 0.0074 | 1.2918 | 0.9314 | | 24.2 | 26 | 23 | 3 |
| ML Vicksburg 2 (aka Vicksburg, MS (WES)) | 0.0000 | 2.3474 | 0.5623 | | 21.8 | 27 | 25 | 2 |



## Individual sites




ML - Vicksburg 1
CBR
CI
12.5
10
7.5
5
2.5
0
0
200
400
600

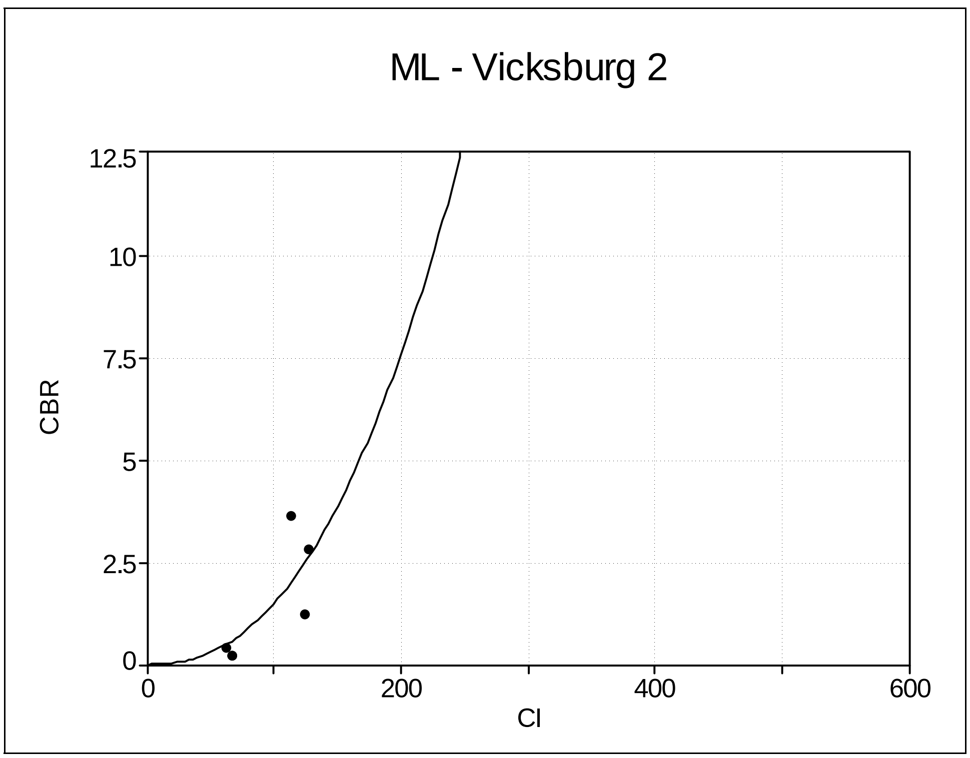
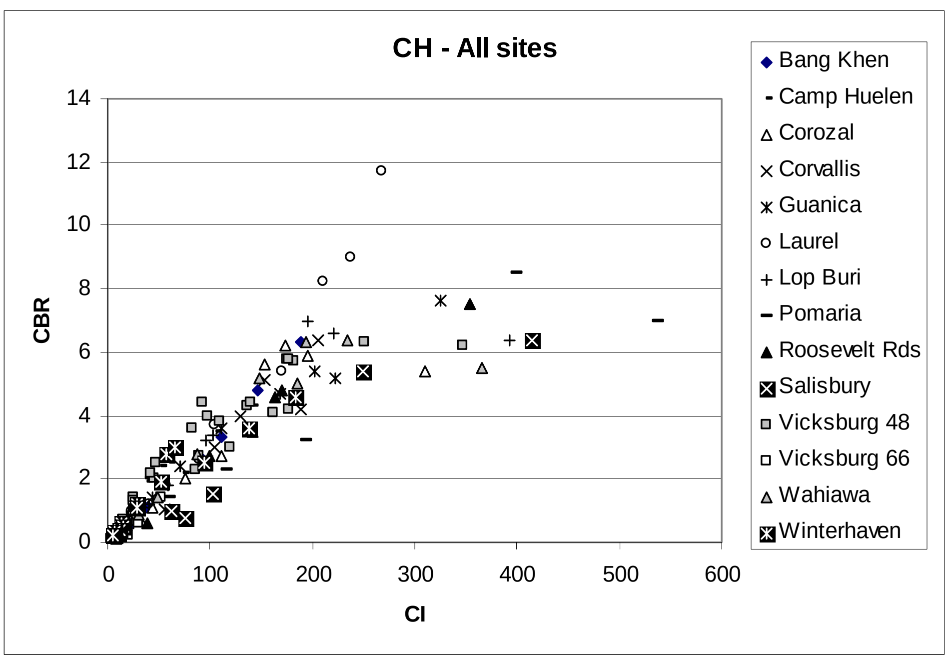
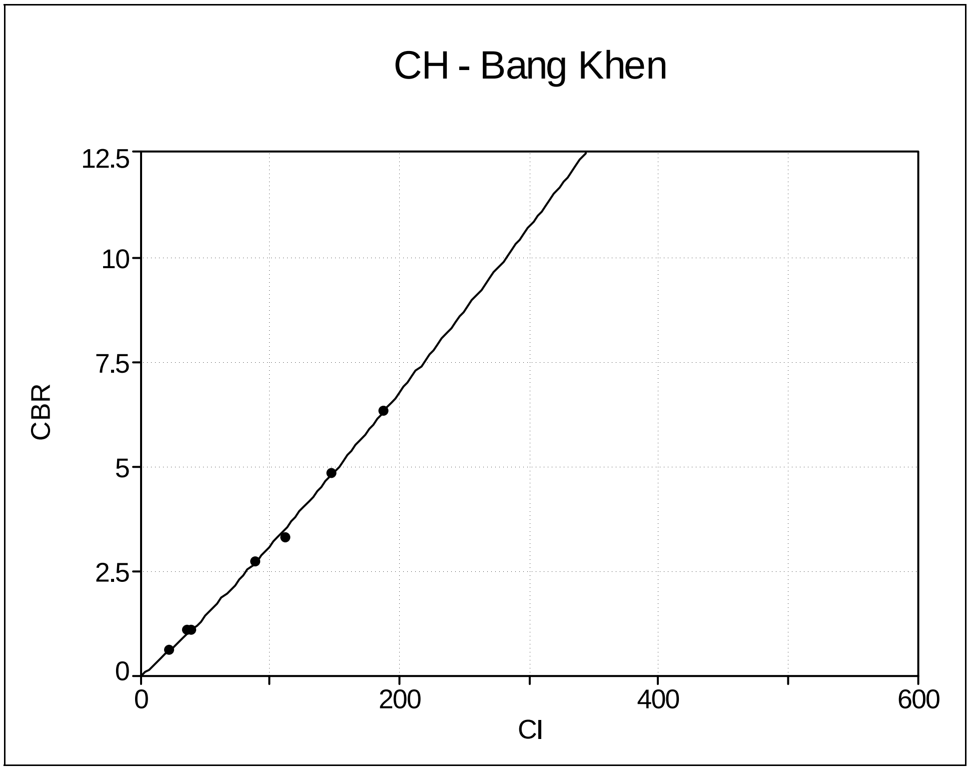

ML - Vicksburg 2
CBR
CI
12.5
10
7.5
5
2.5
0
0
200
400
600

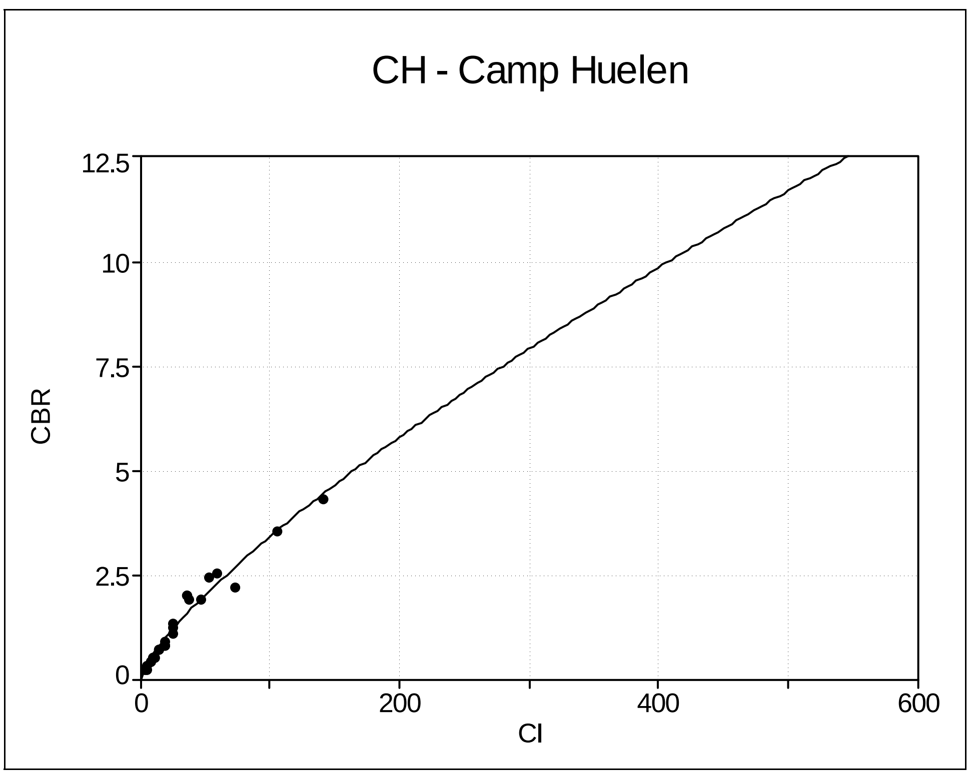
Table D5. CH soils regression coefficients.

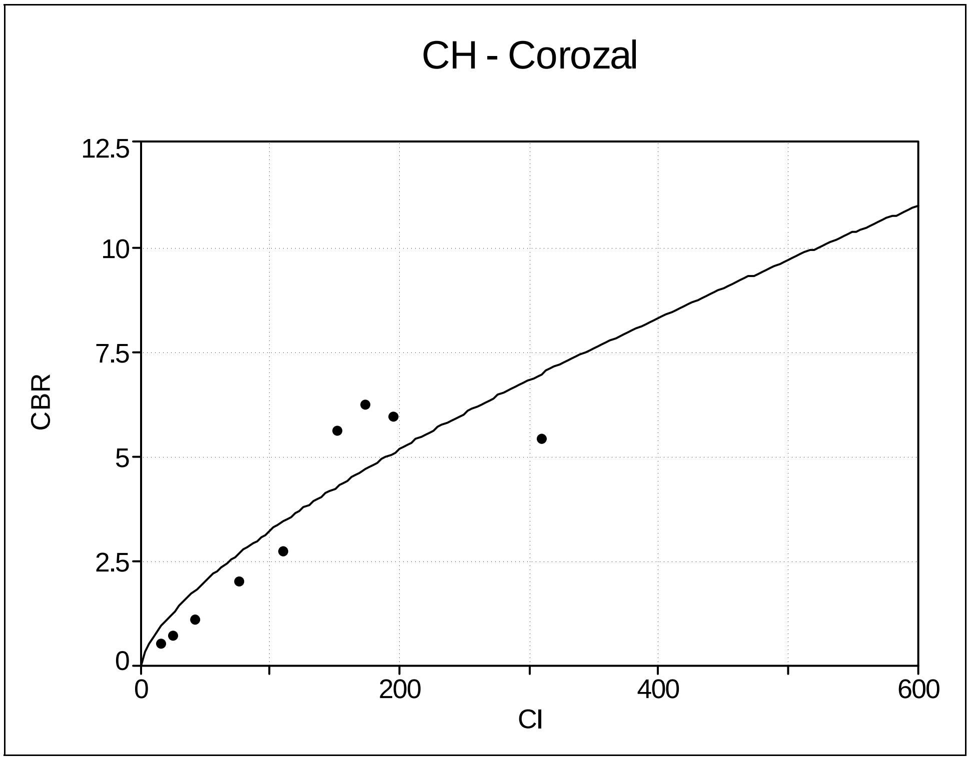
| Soil Type | Coefficients *a* | Coefficients *b* | $R^2$ | Dry Density | MC wt % | Plasticity LL | Plasticity PL | Plasticity PI |
|---|---|---|---|---|---|---|---|---|
| All CH | 0.1264 | 0.6979 | 0.8516 | 78.1 | 41.2 | | | |
| CH Bang Khen | 0.0165 | 1.1349 | 0.9981 | 86.5 | 32.2 | 56 | 24 | 32 |
| CH Camp Huelen | 0.0989 | 0.7674 | 0.9652 | ND | 44.4 | 75 | 26 | 49 |
| CH Corozal | 0.1339 | 0.6882 | 0.8035 | 58.6 | 64.9 | 130 | 48 | 82 |
| CH Corvallis | 0.0245 | 1.0297 | 0.9191 | 75.8 | 41.1 | 66 | 30 | 36 |
| CH Guanica | 0.0738 | 0.8017 | 0.9857 | 68.1 | 50.0 | 90 | 38 | 52 |
| CH Laurel | 0.0088 | 1.2762 | 0.9878 | 77.0 | 40.5 | 81 | 27 | 54 |
| CH Lop Buri | 0.1997 | 0.6142 | 0.8141 | 90.6 | 28.0 | 56 | 19 | 37 |
| CH Pomaria | 0.0627 | 0.7754 | 0.9058 | 85.0 | 32.6 | 55 | 29 | 26 |
| CH Roosevelt | 0.0584 | 0.8348 | 0.9732 | 87.1 | 31.4 | 55 | 28 | 27 |
| CH Salisbury | 0.0221 | 0.9524 | 0.9415 | 91.1 | 28.2 | 50 | 28 | 22 |
| CH Vicksburg 48 (aka Mound, LA) | 0.1510 | 0.6793 | 0.9162 | ND | 36.0 | 67 | 22 | 45 |
| CH Vicksburg 66 (aka Vicks-burg, MS) | 0.0908 | 0.7559 | 0.9083 | 75.5 | 41.0 | 72 | 31 | 42 |
| CH Wahiawa | 0.2269 | 0.5847 | 0.8198 | 75.6 | 44.0 | 71 | 33 | 38 |
| CH Winterhaven | 0.0907 | 0.7585 | 0.9424 | ND | 45.4 | 76 | 25 | 51 |



## Individual sites

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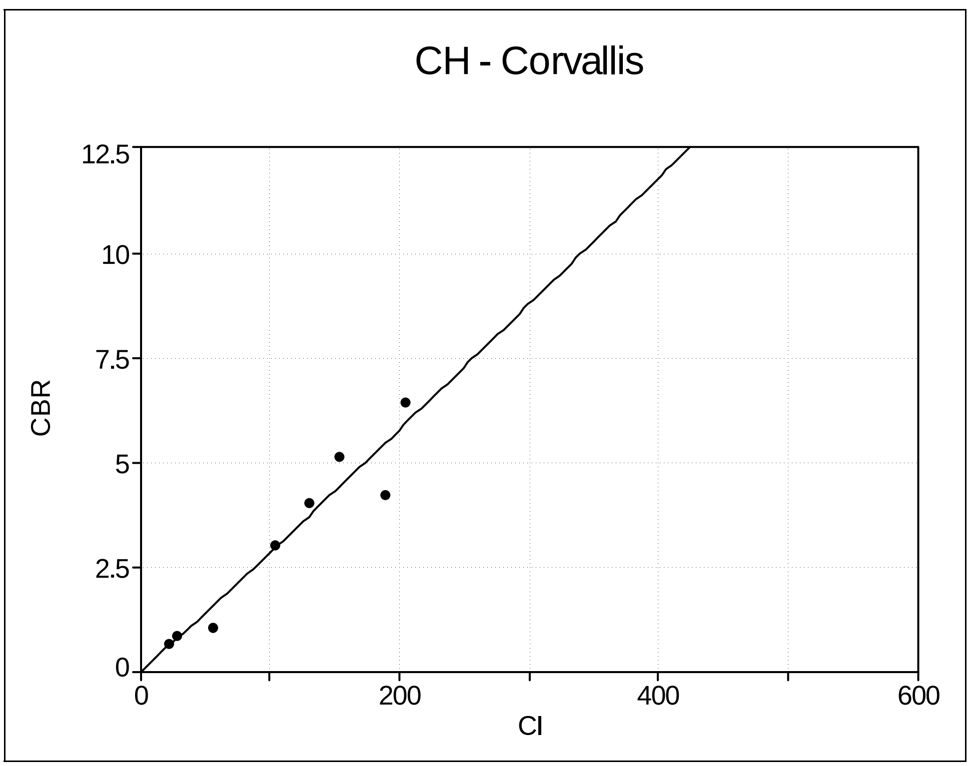
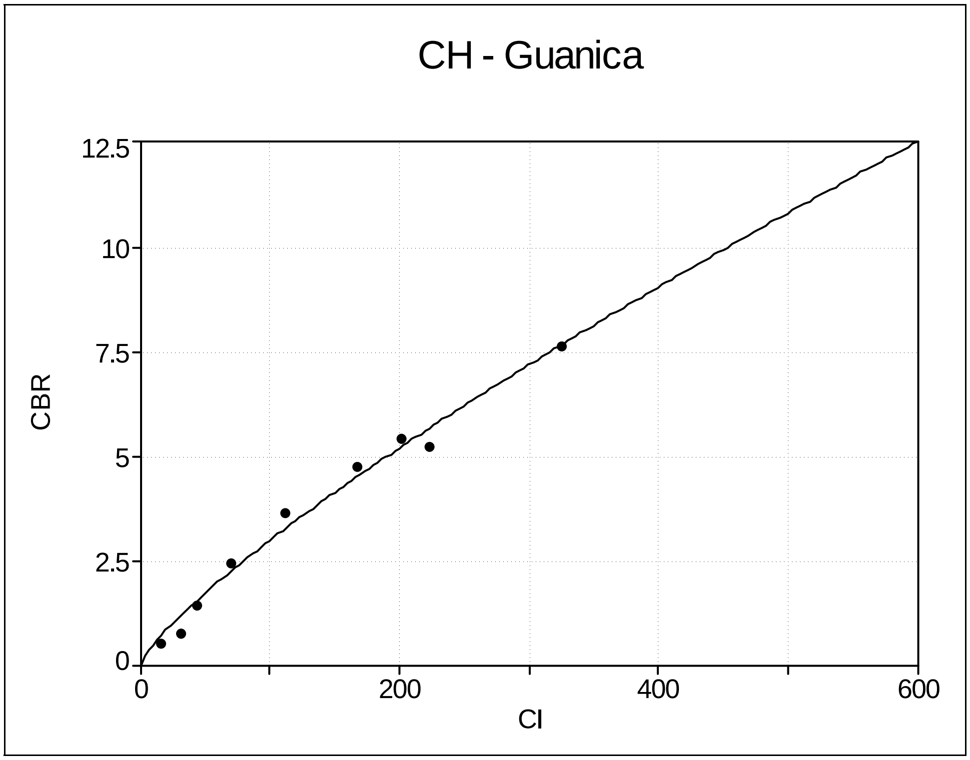
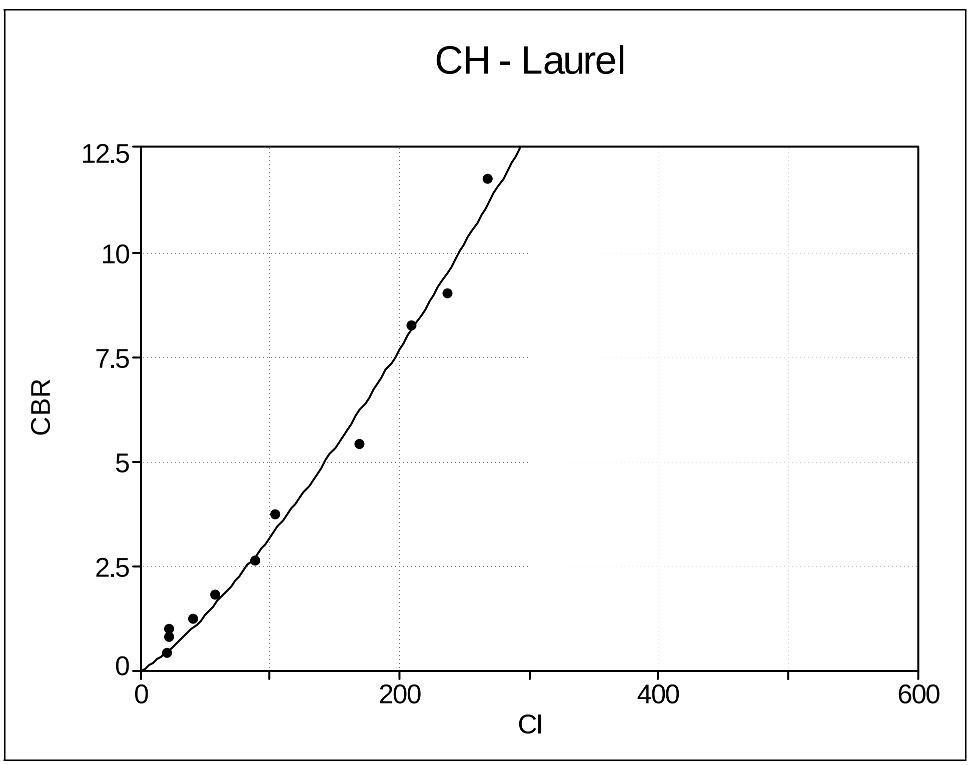
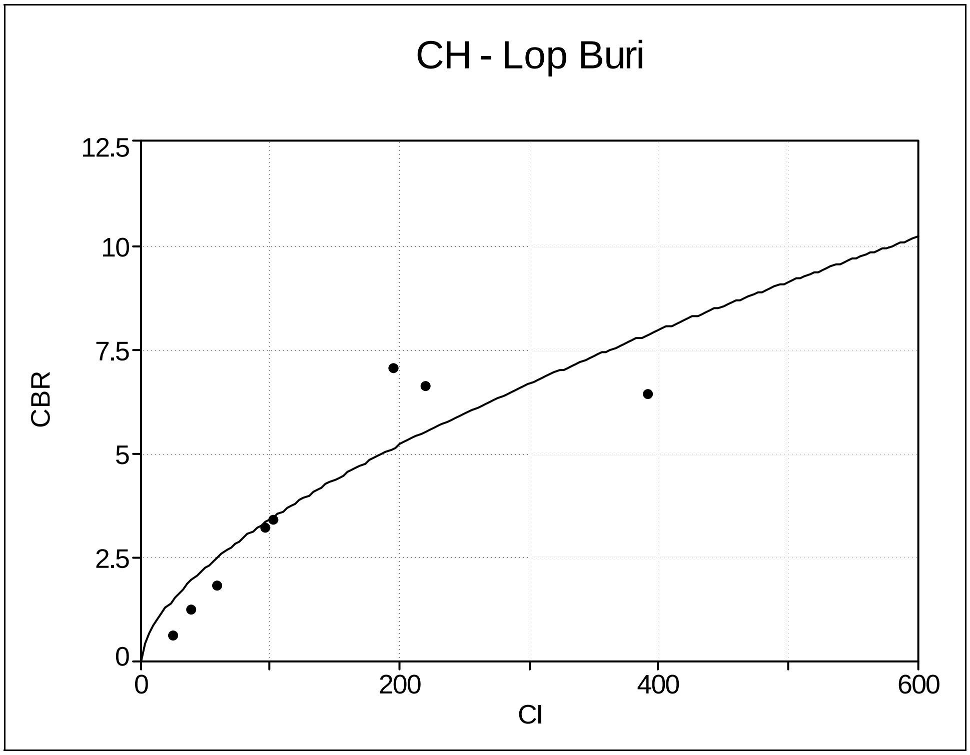
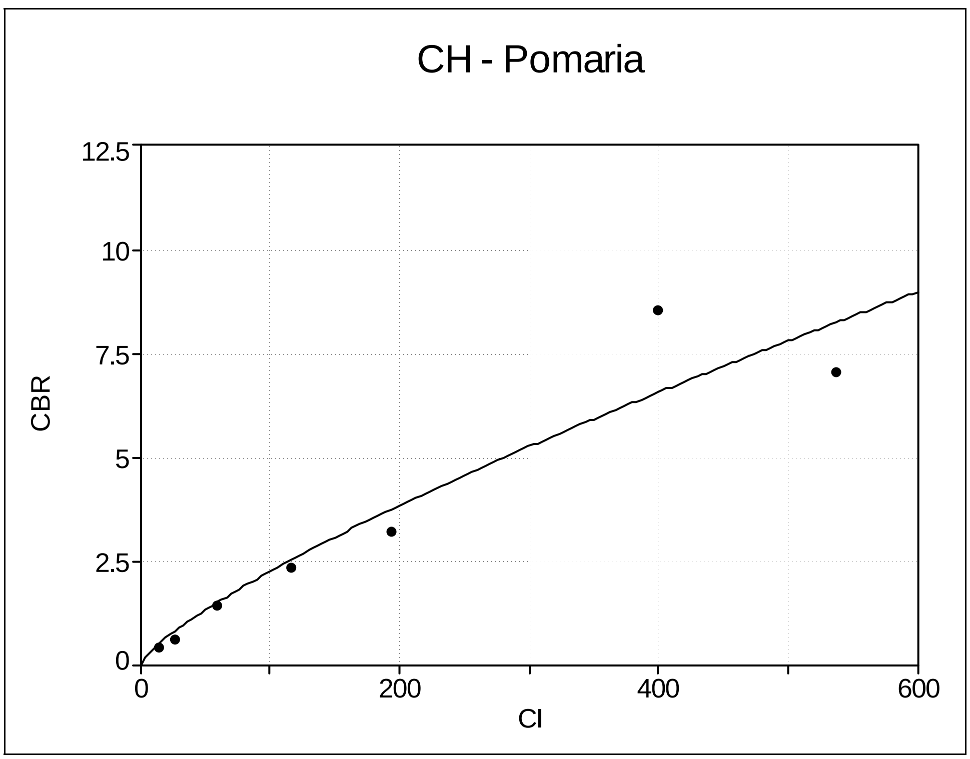
10
7.5
5
2.5
0
CBR
0
200
400
600
CI

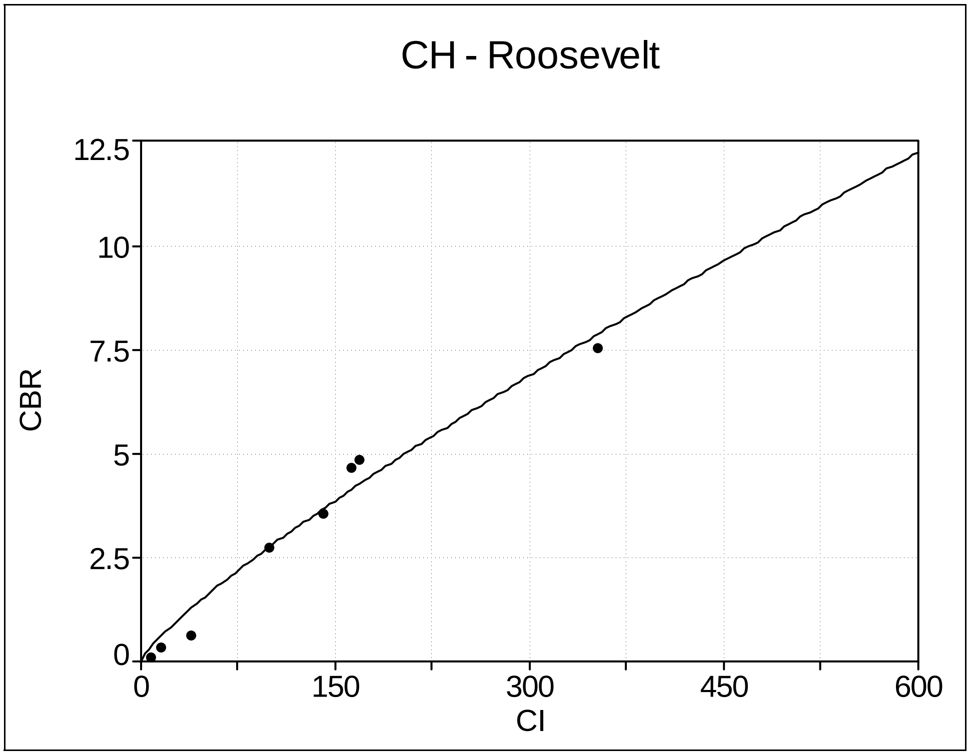

CH - Corvallis
12.5
10
7.5
5
2.5
0
CBR
0
200
400
600
CI

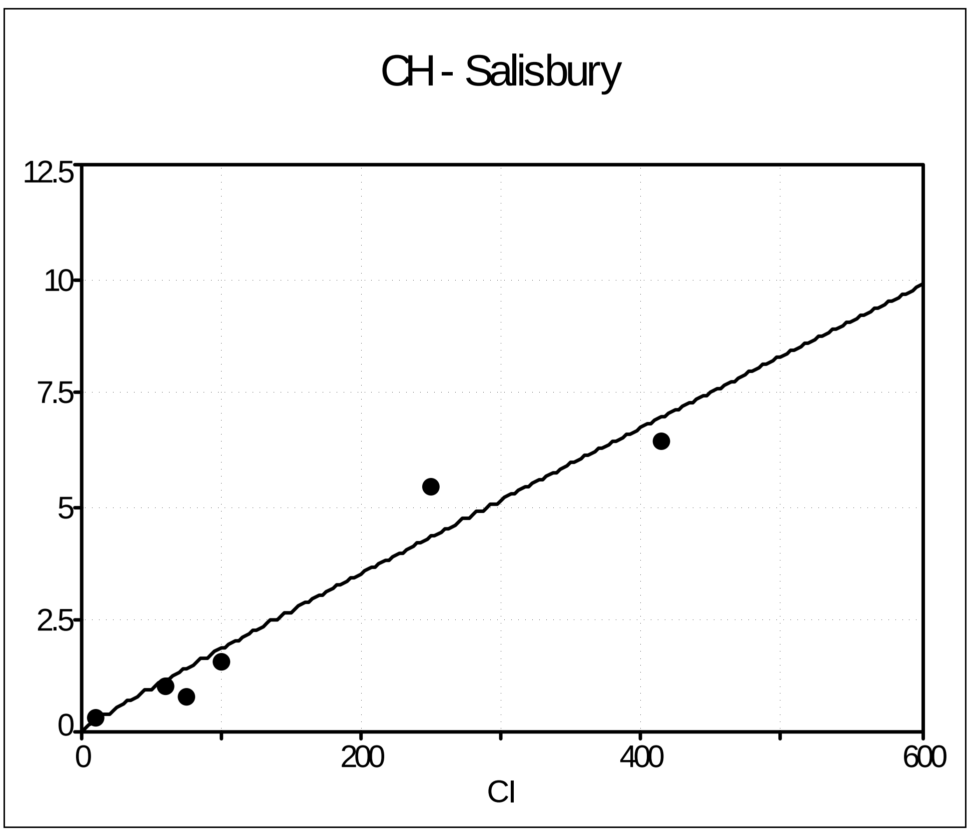

CH - Guanica
CBR
CI
12.5
10
7.5
5
2.5
0
0
200
400
600

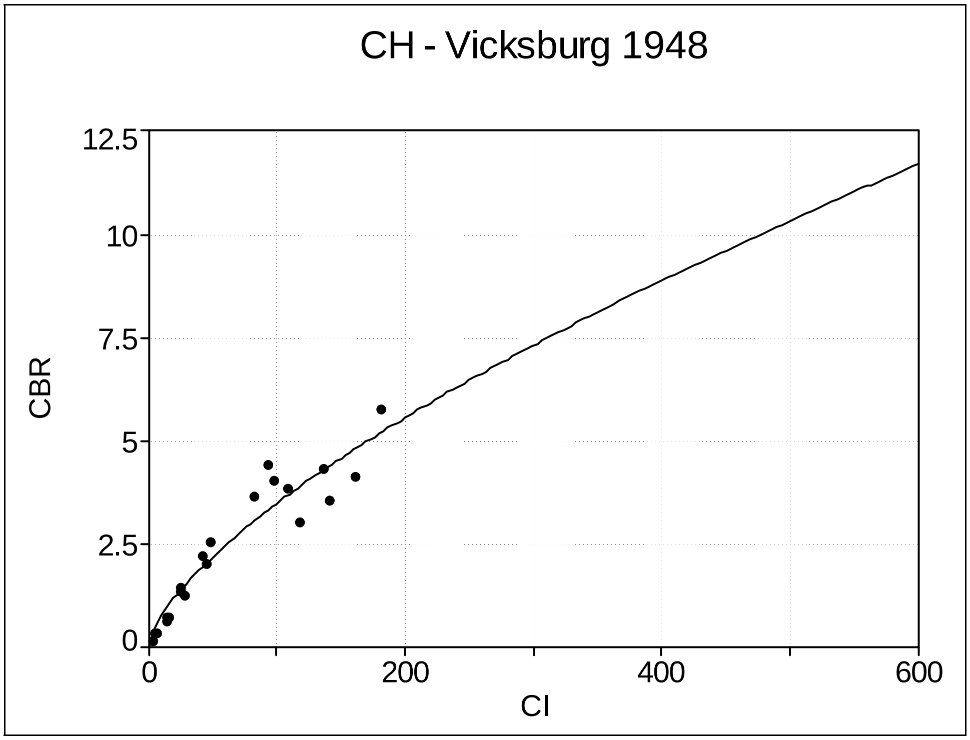

CH - Laurel
CBR
CI
12.5
10
7.5
5
2.5
0
0
200
400
600


CH - Lop Buri
12.5
10
7.5
5
2.5
0
CBR
0
200
400
600
CI


CH - Pomaria
12.5
10
7.5
5
2.5
0
CBR
0
200
400
600
CI


CH - Roosevelt
12.5
10
7.5
5
2.5
0
CBR
0
150
300
450
600
CI


CH - Salisbury
12.5
10
7.5
5
2.5
0
0
200
400
600
CI


CH - Vicksburg 1948
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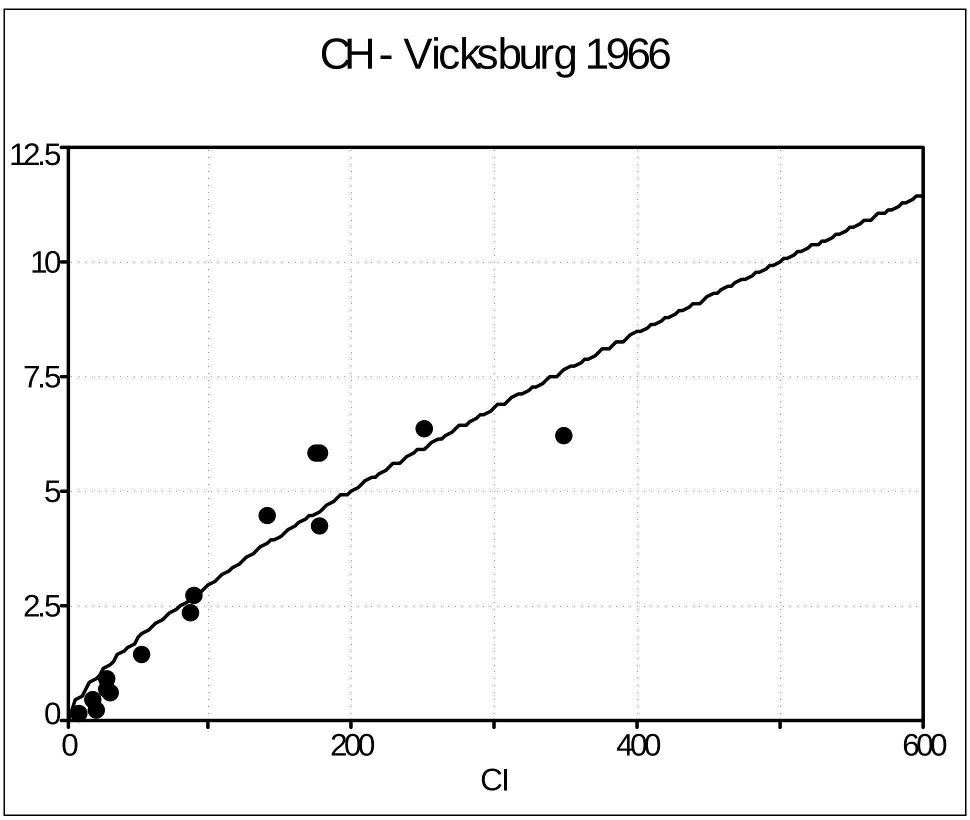
10
7.5
5
2.5
0
CBR
0
200
400
600
CI


CH - Vicksburg 1966
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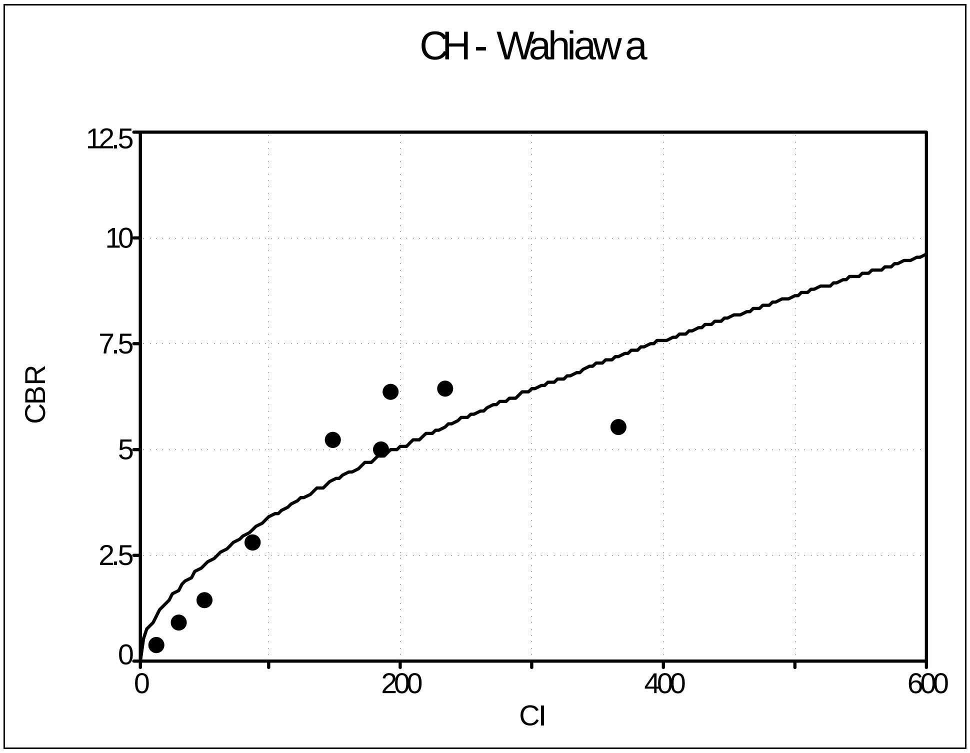
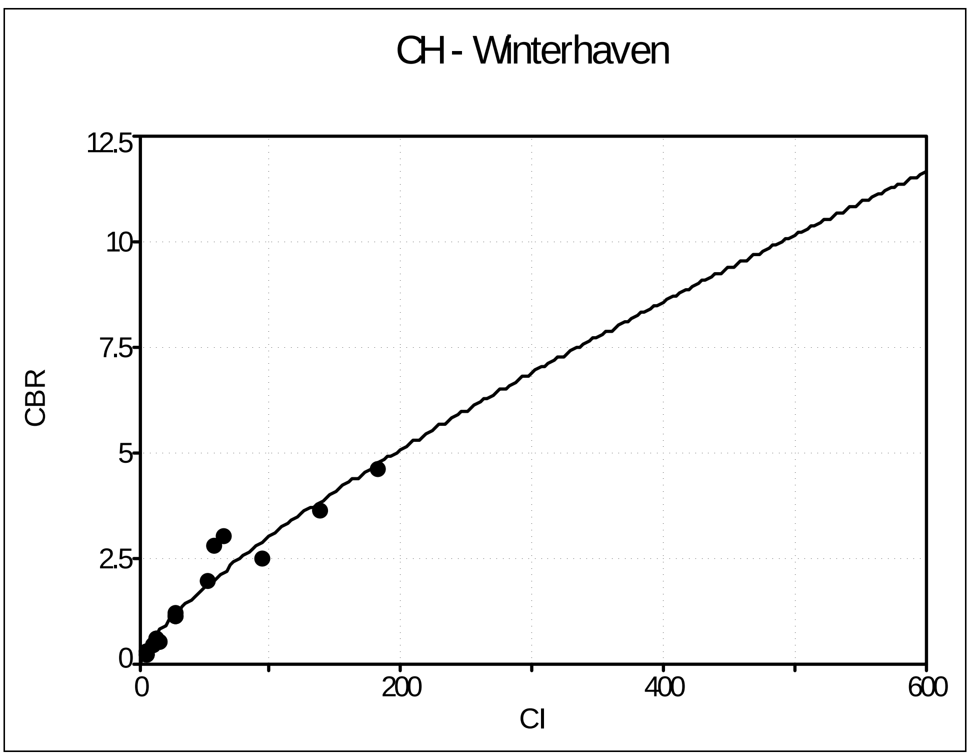
10
7.5
5
2.5
0
0
200
400
600
CI


CH - Wahiawa
12.5
10
7.5
5
2.5
0
CBR
0
200
400
600
CI


CH - Winterhaven
12.5
10
7.5
5
2.5
0
CBR
0
200
400
600
CI

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## 14. ABSTRACT

California bearing ratio (CBR) soil strength measurements are commonly used by the U.S. Air Force to identify locations suitable for use as expedient runways. Field CBR testing is a time-consuming operation requiring a skilled operator, and can be hazardous for the evaluation teams in hostile environments. Limited amounts of published CBR data are available. The measurement of trafficability cone index (CI), widely used by the U.S. Army for similar applications, is a process that is fast and simple, and for which a vast amount of published data worldwide are available. This report describes methods reported in the literature to correlate CBR to CI based on Unified Soil Classification System (USCS) soil type, as well as a systematic program to develop an algorithm to predict CBR from CI using a database of measurements of both CBR and CI made concurrently by the U.S. Army, many of which were taken in undisturbed soil. The database is described and related soil properties, such as plasticity information, soil density, specific gravity, and moisture content, are given.

**15. SUBJECT TERMS**
OLS, Opportune Landing Site program, soil, strength, bearing capacity, trafficability, cone index, CI, California bearing ratio, CBR, prediction

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